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SERENDIPITY AND THE DEVELOPMENT OF EXPERIMENTAL  
METEOROLOGY<sup>a</sup>

By Vincent J. Schaefer<sup>1</sup>

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SYNOPSIS

The scientific developments leading to the discovery of cloud-seeding are described. The difficulties and importance of understanding mountain meteorology are presented. Improvements in forecasting of weather phenomena are to a large extent dependent on such an understanding. The engineer's role in experimental meteorology is explained.

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Down through the centuries, man has had a persistent dream—the ability to control the weather.

These thoughts probably began when long droughts, bad floods, or similar weather developments threatened him and his family with starvation, thirst or other grim troubles. By incantation, sculpturing of rain gods, and other mysterious maneuvering, the "medicine man" hoped somehow to influence weather.

Man has not changed much since these primitive times. One of his major complaints or topics of general conversation concerns the weather. Although he now has many ways to modify his local climate, using central heating, air conditioners, and other artificial aids, he is still essentially at the mercy of the tornado, the hurricane, the drought, the flood, and the hot and cold waves of summer and winter.

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August 1959 Weather Modification Conference in Denver, Colo.

<sup>1</sup> Research Consultant, Schenectady, N. Y.

He still dreams—and, gradually, with the acquisition of scientific knowledge, his hope has intensified that something might be “done” about the weather.

Whether he and his neighbors could ever agree as to what should be done, is a problem which may become as troublesome as his struggle to cope with the elements. Until it is determined what could be done, most arguments on this particular subject are wasted time. This does not mean that he will not indulge in such discussions, however!

It was more than twenty-five years ago when the writer first heard the word “serendipity,” while visiting the laboratory of Willis R. Whitney, famed for his pioneering, organization, and development in Schenectady, N. Y. Whitney was a great believer in the experimental approach for solving problems of a scientific nature, especially in relation to the discovery of entirely new phenomena which often lead to the establishment of entirely new areas of scientific knowledge.

As a young research assistant, the writer was privileged to build equipment for him, and subsequently for one of his great “finds”—Irving Langmuir.

Both Whitney and Langmuir were great experimentalists and firm believers in the importance of serendipity<sup>(3)</sup><sup>2</sup> in the progress and development of science.

While the word serendipity has been rather narrowly interpreted as the “art of profiting from fortunate accidents,” or, more elegantly, “the process of profiting from unexpected occurrences,” there is another aspect of this basic phenomenon that often controls our role in science over considerable periods of time. This is a combination of serendipity in the above sense of the word, combined with the intuitive exploitation of fortuitous developments occurring in a chain of seemingly unrelated events but often converging and leading to what seems to be a logical objective or end point.

Such were the series of events, before, during, and after World War II, that led into the field of experimental meteorology, cloud modification, and certain aspects of weather control. Basic and applied research in the atmospheric sciences will lead to many instances where serendipity, in the broadest sense of the word, and its intelligent utilization will play an extremely important and valuable role as more and more unbiased, enthusiastic and uninhibited scientists become involved in exploratory studies of this fascinating field of science.

The first large-scale scientific effort to explore the possibilities and limitations of weather modification started early in 1947, and was called Project Cirrus. Sponsored by the United States government under joint Army and Navy assistance, with aircraft supplied by the Air Force, and guided by a small group of scientists from a research laboratory, Project Cirrus, was destined to provide a major stimulus to the development of the new branches of weather science dealing with atmospheric and cloud physics and experimental meteorology.

The scientific developments leading to the start of these activities had a complex though interesting background.

Prior to World War II, Langmuir and Vincent J. Schaefer were conducting fundamental research in surface chemistry with particular emphasis on single and multiple molecular layers of organic materials such as proteins, chlorophyll, fatty acids, and synthetic resins.<sup>(4)</sup>

Early in 1940, Langmuir and Schaefer agreed to devote time to studies of gask-mask filters. Special emphasis was needed on theoretical and experimental studies of filters designed to remove small particles from moving air.

<sup>2</sup> Numerals in parentheses, thus (1), refer to corresponding items in the bibliography.

The knowledge and experience acquired by Langmuir and Schaefer over the previous years in the field of surface chemistry were of great assistance in the development of techniques for handling, experimenting with, and measuring fibers in the range of 1 to 10 microns and smoke particles in the range of 0.1 to 1 micron. Such dimensions are a thousand to ten thousand times greater than those encountered in dealing with cross-sections and single layers of molecules. Many experiments were conducted during 1940, in the development of new types of efficient filters based on both experimental and theoretical grounds.(5)

In the course of the smoke-filter study, a request was received from Washington for ideas or methods that might be utilized in forming screening fogs for obscuring cities, troop movements, etc., from air observation and attack.

In the course of testing the efficiency of experimental filters, Schaefer had constructed several devices for making uniform smoke particles. It was decided to construct larger units of the several different types to explore the feasibility of making screening smokes on a large scale. As a result of these trials, two basic methods were devised, both of which were dependent on the rapid growth of smoke particles in super-saturated oil vapor. The oil used was characterized by a very low vapor pressure at ordinary temperatures.

The unit based on passing the oil through a fire zone to achieve vaporization was discarded in favor of one which utilized a continuously fed flash-type boiler. With this method, the oil was heated rapidly until it boiled and developed about ten pounds of pressure. An orifice of specific size permitted the oil vapor to escape from the boiler to the atmosphere. The resulting jet had sonic velocity with several inches of the stream outside the orifice showing a transparent vapor (Fig. 1). Condensation occurred beyond this point, with the particles formed by supersaturation. After condensing, the particles started to grow very fast, but rapid mixing with the surrounding air arrested further growth within a few milliseconds. Since the oil used had a boiling point of over 400° C, its vapor pressure at normal air temperature was so low that evaporation was negligible even after many hours. In this manner, a very satisfactory screening smoke was produced. Studies of the light scattering properties of such oil smoke showed that the most effective particle size for screening purposes in the visible range was a diameter of about 0.6 microns. It was found by both experimental and theoretical studies that particles of this size were easily formed by condensation phenomena at the rate of  $10^{14}$  sec<sup>-1</sup> with a momentary concentration of particles in excess of  $1 \times 10^{12}$  per cu cm. The rapid quenching of the supersaturated vapor previously mentioned permitted the formation of colossal numbers of particles with a remarkable uniformity of size. As finally developed, the large generators were fitted with a manifold containing ten nozzles which formed smoke particles from 100 gal of oil per hr (Fig. 2).

Field studies of 10 gal per hr and 100 gal per hr generators were conducted in the Schoharie Valley, southwest of Schenectady, south of Vrooman's Nose, the top of which was used as a stable platform for observation purposes. Early morning temperature inversions were utilized for spreading the smoke in a blanket of uniform thickness over the flat valley floor. Still and time-lapse motion picture techniques were utilized for making quantitative evaluations of the screening properties of various types of smokes, and on June 25, 1942, a successful large-scale demonstration (Fig. 3) was conducted for military and civilian personnel concerned with this problem. Following this demonstration, the engineering development that led to the large-scale use of the generators during the war was taken over by various commercial organizations.(6)

In addition to providing much useful experience concerning the manner in which particles grow and may be measured, the smoke generator study was invaluable in supplying a wealth of experimental knowledge in micrometeorology, the optical properties of artificial fogs, the persistence and breakdown of early morning atmospheric inversions, the electrical effects produced by particles of nonuniform size moving at varying velocities, and related phenomena. In the course of this work, Langmuir and Schaefer were helped on special phases of the work by Katharine Blodgett, Arthur Gregg, and Clarence Nelson, M. ASCE.

Starting early in 1943, and continuing for about 1/2yr, Langmuir and Schaefer

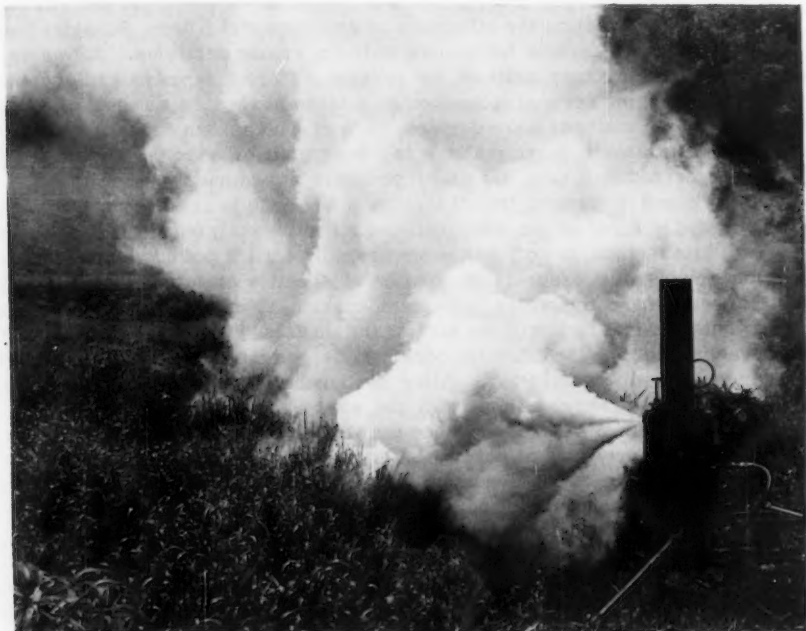


FIG. 1.—VIEW OF ORIGINAL 10 GAL. PER HR. SCHAEFER-LANGMUIR SMOKE GENERATOR.

worked with Edward F. Hennelly on a submarine-detection problem involving a simplified binaural listening device.

Early in the fall of 1943, a problem related to aircraft radio static was presented to Langmuir and Schaefer by the Air Force, with the expressed hope that they work on some of the basic causes of such trouble. Because of their interest in snow and meteorology, this proposal was accepted, and for the next year an intensive study was conducted by a small group of the laboratory in both field work, at the Mount Washington Observatory and Schenectady, and in aircraft flights in various regions. Besides Langmuir and Schaefer, Messrs. Elliot Lawton, Hubert Tanis, and Albert Fiumara were involved in the laboratory and field activities during this period.(7)

During the studies at the summit of Mount Washington, it was soon realized that, although the mountain was an excellent site from the standpoint of frequent storms and high winds with much blowing snow, a serious limitation was present for precipitation static studies, owing to the almost invariable presence of supercooled clouds whenever storms occurred. Within a few seconds after sample wing sections or other static collectors were exposed, they became coated with a layer of ice from the deposition and freezing of the supercooled cloud droplets. Since the problem under study was the charging mechanism related to the impact of snow-crystals on aluminum coated with wax or camouflage paint, and not on ice coated surfaces, the mountain was found to have



FIG. 2.—VIEW OF LARGE SMOKE GENERATOR IN OPERATION.

certain limitations for this particular study.

Fortunately, a large number of snowstorms occurred at Schenectady during the winter of 1943-44, so that adequate test periods were available to complete the project.(8)

The deposition of ice on all exposed objects at the summit of Mount Washington, illustrated in Fig. 4, involved many fascinating unsolved problems related to the physical nature of supercooled clouds. Thus, within a very short time, Langmuir and Schaefer became actively involved in these interesting problems. Personnel of the U. S. Air Force Equipment Laboratory were anxious to have basic research carried out in this field, and proposed that Langmuir and Schaefer undertake research along these lines. In this manner, the transition



FIG. 3.—ARTIFICIAL FOG PRODUCED

from snow static studies to the study of supercooled clouds was made without loss of time, since the problems were complementary to each other. The change in emphasis was a gradual one, since many aspects of the two problems were inseparable.

A very active program in basic studies of the properties of supercooled clouds took place during the next several years. Many new techniques were devised; others in current use were improved, resulting in a new approach to the aircraft icing problem.(9)

The importance of Mt. Washington as a site for making icing studies was brought to the attention of military personnel by this activity. The inauguration of Project Summit, the jet engine-icing research project sponsored by the Navy Bureau of Aeronautics, and the current plans for constructing a large experimental laboratory by the Air Force on Mt. Washington stem from this activity, which was started in 1943. In all of these activities, officers and personnel of the Mt. Washington Observatory played a key role, and much credit should be given to this remarkable institution for many advances that have occurred in the field of cloud physics and aircraft icing research.(10)

By the end of 1945, Langmuir and Schaefer were beginning to shift their interest from aircraft icing projects to the more basic problem of the nature of supercooled water.

This involved a two-fold approach—the observation of natural clouds in the atmosphere and a laboratory study of methods for causing and preventing the formation of supercooled water. The initial work on the former was carried out at Mt. Washington and in the Mohawk Valley in eastern New York, while the latter problem was approached from surface chemistry relating the effect of



IN SCHOHARIE VALLEY IN 1941.

various types of molecular surfaces on the development and persistence of condensed supercooled water droplets.

After several months had been spent in work with supercooled droplets on many types of surfaces, a change in approach was afforded Schaefer by the acquisition of a cold chamber with a capacity of 4 cu ft, in which a supercooled cloud could be formed in a very simple and convenient manner. Since the clouds that could be formed in this manner were identical in most respects to small sections of natural clouds in the atmosphere, the means were thus available to make rapid progress in studying the nature of supercooled clouds.

Early in July, 1946, Schaefer was working with the supercooled clouds in a cold chamber. It was a hot, muggy day, and as successive clouds were formed in a continuing series of experiments, aimed at causing the droplets to freeze by introducing various types of chemicals and dusts into the cloud, he noticed the temperature of the air of the chamber warming to the point of being ineffective for forming a cold cloud. Rather than to stop the experiment, he decided to help cool the chamber with some large chunks of dry-ice. The instant the dry ice was placed in the chamber, he noticed a complete change in the nature of the cloud. He knew at once that he had reached his goal. Here was a perfect example of serendipity. While the introduction of the dry-ice into the chamber was for an entirely different purpose, the effect it produced was the one he had been searching for over a period of several months.

Immediately Schaefer removed the dry ice, again formed a supercooled cloud, and found that only the tiniest bit of dry ice was necessary to cause a profound and highly spectacular effect in a supercooled cloud.(11) He then found that any material colder than  $-40^{\circ}\text{C}$  would produce the same effect—cold

metal, liquid nitrogen, or any substance producing a momentary cold zone in the presence of air containing enough water to make it slightly supersaturated with respect to ice. Quantitative studies showed that at least  $1 \times 10^{16}$  ice-crystals could be produced under optimum conditions with 1 gm of dry-ice.

The reason why other investigators in the past did not discover the properties of dry ice or other colder than  $-40^{\circ}\text{C}$  substances in producing homogeneous nucleation of ice crystals is, also, probably attributable to a lack of a serendipitous situation. Both L. Gathman(12) in 1891, and A. W. Veraart(13) in 1931, had used dry-ice in air and in clouds. Both persons had the idea that the chilling of air would produce clouds and cause large effects in the atmos-



FIG. 4.—RIME DEPOSITS ON AIRCRAFT WING CROSS SECTION. MT. WASHINGTON.

phere. They completely failed to recognize the importance of the triggering effect of dry ice in changing the phase of a supercooled cloud. The time was not ripe or they were following a line of reasoning that did not permit them to recognize the importance of phase changes and related phenomena.

Within a short time after discovering the dry-ice effect, plans were made to explore the possibilities of modifying supercooled clouds in the atmosphere. As so often happens with experimental operations with weather in the atmosphere, the ensuing period was virtually cloudless for a long period.

Finally, on November 13, 1946, an extensive system of lenticular clouds occurred. One of these was seeded by Schaefer from a small chartered plane flying in the vicinity of Mt. Greylock in the Berkshires of western Massachusetts. The conversion to ice-crystals was spectacular, both at close range and as

seen from the Schenectady airport nearly 50 miles away.(14) The appearance of the cloud before and after seeding, as photographed by Schaefer, is shown in Fig. 5.

Eight days later, a supercooled valley fog was also seeded by Schaefer, with striking results. The fog, which had been supercooled, was effectively overseeded in localized areas by dry-ice seeding. This reduced the visibility to a considerable degree, as shown in Fig. 6. About 15 min later, an area on either side of the overseeded region was seen to clear as smaller numbers of crystals caused the supercooled droplets to evaporate and precipitate as diamond-dust.

Several more flights were made by him in a chartered plane in November and December, 1946, during which it was found that:

1. A supercooled drizzle falling from an extensive cloud system was completely modified, and a local snowstorm of moderate intensity was apparently initiated in the Hudson and Champlain Valleys.
2. The feasibility of seeding below the base of cumulus clouds with liquid carbon dioxide was demonstrated.
3. Extensive grooves could be cut into a deck of supercooled stratus clouds by using about a pound of dry-ice per mile of flight.
4. Supercooled cumulus congestus could be modified to a remarkable degree by small amounts (one pound lots) of crushed dry-ice, producing local snow showers.
5. Precipitation could be initiated in standing wave-clouds by seeding the upwind side of the cloud, but the seeding had to be continuous if precipitation was to continue.

As a result of the positive results following all experiments, and realizing the possible importance of the use of widespread applications of experimental meteorology, effort was made to interest the government in continuing active research in a manner not possible for various reasons by members of the research laboratory.

Meanwhile, Bernard Vonnegut, who had previously worked in the field of gas-mask filters and aircraft icing, while at the Massachusetts Institute of Technology, became interested in the general field of research being pursued by Langmuir and Schaefer and joined forces with them. Vonnegut proposed using a substance for seeding supercooled clouds that would have the same crystalline structure as ice. A search of the literature showed silver iodide to be the most suitable substance for this purpose. Initial trials failed, although iodine and iodoform seemed to be reasonably effective. Within a short time Vonnegut found(15) that the silver iodide supplied to him had been improperly prepared. A better sample worked beautifully. It was later found that the iodine worked by reacting with metallic smoke particles present in the laboratory air, which formed iodides.

Thus, by the time a contract was obtained with the U. S. Army Signal Corps, in cooperation with the office of Naval Research, on February 28, 1947, the research laboratory group, then consisting of Langmuir, Schaefer, Vonnegut, Robert Smith-Johannsen, Raymond E. Falconer, and Kiah Maynard, had many projects in mind for continuing an active program of laboratory, field, and flight studies related to various phases of experimental meteorology.

This program continued from February 28, 1947, to September 30, 1952, during which time many interesting projects were carried out in eastern New York, Puerto Rico, the Southwest, and other parts of the world.



FIG. 5a.—VIEW OF SUPERCOOLED CLOUD BEFORE SEEDING.



FIG. 5b.—VIEW OF SEEDDED CLOUD CONVERTED TO SNOW CRYSTALS BY DRY ICE SEEDING.

The story of Project Cirrus, and the many interesting developments that followed(16) in the fields of atmospheric physics, chemistry and electricity, has been described in many papers.(17-24) The papers presented at the Weather Modification Conference in August, 1959, illustrate very well the advances that have occurred during the past few years, as well as the uncertainties still with us. Perhaps the most significant paper presented at this meeting is the one by D. M. Fuquay(25) which describes a major advance in cloud seeding generator technology. A single Fuquay-Wells Generator is now capable of an output efficiency equivalent to a hundred of those currently in use. For the first time, it may be possible to conduct overseeding of large convective clouds by a single airplane operation. Only time will show how important this new tool may be.

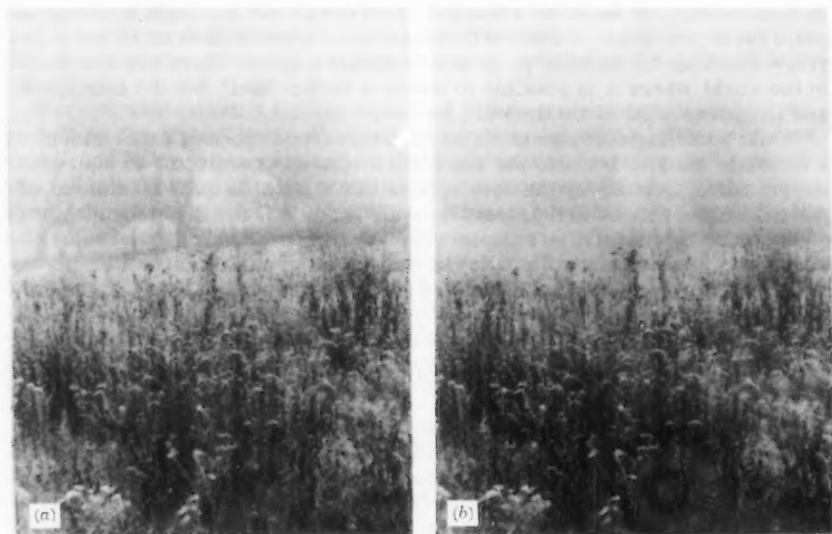


FIG. 6.—CONVERSION OF SUPERCOOLED GROUND FOG TO ICE CRYSTALS USING DRY ICE SEEDING.

As progress is made in the conduct of fairly large scale (mesoscale in actual size) seeding activities, many problems of measurement, technique, and atmospheric behavior are confronted. In some instances it is necessary to return to the laboratory to search for new ideas in an attempt to understand some of the basic mechanisms of cloud physics and related phenomena. Perhaps the technique which will yield the most rapid and useful returns from the research effort will be in the intelligent use of mountains as a sort of laboratory bench. Only by dealing with fairly massive interactions may it be hoped to get a proper perspective on some of the problems confronted. The mountain slope and summit and a proper understanding of their role in the atmosphere should give valuable ideas and suggestions for further experimentation. A new look should

25 "General Technology for Cloud Seeding," by D. M. Fuquay, (To be Published).

be taken at the mountain observatory as a highly important and inexpensive site for probing the atmosphere.

The real value of a mountain observatory is probably most appreciated by those who have tried to wrest secrets from the atmosphere while using airplanes. There is nothing quite so satisfying, after such experiences, as a firm and stationary platform for holding weather-sensing instruments. While mountain summits have their limitations as atmospheric probes, they have some distinct advantages, many of which have not been properly recognized or even understood.

There is probably no better place in the world than a mountain top for a young person to become acquainted with the atmosphere. The writer has a firm belief that a period of two or three months spent at a mountain observatory should be a firm requirement for qualifications to receiving a master's degree in meteorology. It would do a world of good for all meteorologists, young and old, research-minded or routine forecasters, to spend a week or so every few years watching the weather go by at a mountain station. There are few places in the world where it is possible to obtain a better "feel" for the atmosphere and an appreciation of the dynamic forces it contains.

While some meteorologists object to using certain types of data obtained at a mountain station, because the mountain might exaggerate the wind, reduce the pressure, or intensify the development of clouds, it is quite feasible to adjust such observations to represent free-air conditions and thus take advantage of the more representative sample which is measured there, than can be obtained at a weather station on a lowland air port or city center where the atmosphere is often highly artificial and not at all the same as that of the surrounding countryside.

#### IMPORTANCE OF UNDERSTANDING MOUNTAIN METEOROLOGY

A proper understanding of the meteorology in mountainous regions has not been achieved thus far. It is a difficult subject but one with fascinating and challenging aspects. The data from a mountain observatory, especially if combined with simultaneous observations from nearby valley stations, such as is the case at Mount Washington, could go a long way toward solving some of the major problems in meteorology related to phenomena such as convergence, jet currents, cloud growth, air trajectories, heat sinks and heat sources, and other effects having dimensions which fit most properly into the scale of micro and meso-meteorology. Such effects, however, must be better understood if it is hoped to ever properly understand weather phenomena on the continental and global scales. When seen in proper perspective, (and one needs only to go up 40,000 ft in the air to appreciate it) our weather occurs in an extremely shallow layer over the surface of the earth. Because of this thin layer, many atmospheric reactions can be properly characterized as interfacial phenomena, and for this reason the controlling factors are often not far away. Until more is learned about the cause and effect relationships of weather systems over an area such as is represented by New England, there will probably be little progress made toward improving weather forecasts or knowing the reasons why they sometimes fail.

The characteristics of the atmosphere contacting a mountain slope or summit is everchanging. The problems involved in measuring these properties are not simple ones, nor are they insurmountable. With the amazing advances in instrumentation that have occurred over the past 10 yr, rugged, nearly fool

proof, and relatively inexpensive devices are becoming available which hold promise of simplifying the job of measuring the properties of the atmosphere in isolated places. If properly exploited and carefully planned, unmanned weather stations might easily supplant most of our current weather network. Such changes should be welcomed by all progressive meteorologists, since it would permit them to spend their time on research and other constructive activities. The accomplishment of these objectives is at present primarily an engineering job—but—not one for the faint hearted!

When the importance of mountain summits is properly recognized, certain key mountain observatories will have highly important roles to play. Some, such as the Mount Washington Observatory, N. H., Whiteface Mountain Observatory, N. Y., the White Mountain Observatory near Bishop, Calif., and the solar observatories at Climax, Colo. and Sun Spot, N. M., being easily accessible, could serve a dual role encompassing both science education and research, with the former being emphasized during the summer tourist season, the latter from fall to spring when the mountains are almost as isolated as if they were in the polar regions.

More remote summits such as are found in the equatorial regions of Africa, the subtropics of Hawaii, the West and East Indies, the middle latitudes of Asia, Europe and western America, and the polar plateaus of Greenland and Antarctica could yield highly valuable scientific information on subjects for which each place possesses unique characteristics. Research facilities in many of these areas are no longer difficult to establish or support. The development of air travel, cargo dropping, and related techniques, perfected during and since the last war, make such remote areas easily accessible to scientists. While these advanced technologies have become available, meteorologists have been painfully slow in making adequate use of them. Perhaps it is time that new disciplines are brought into the picture to show the possibilities in using such areas for atmospheric probes.

#### ENGINEER'S ROLE IN EXPERIMENTAL METEOROLOGY

What phase of experimental meteorology is likely to appeal to the engineer? There are few sciences where engineering talent has greater or more challenging opportunities. The pay-off may be slow, but it is likely to be very worthwhile.

Despite the continuing but rapidly abating controversy of the effectiveness of precipitation control and cloud modification, many cloud seeding operations have reached routine operational status where the engineer can begin to take a more active role. This is not to say that the job is nearly done. Rather the manifold possibilities are just now being vaguely recognized.

Although considerable effort has been directed toward the development of adequate sensing and recording equipment for atmospheric research, much of the gear now in use is still bulky, inadequate, and, in too many cases, unreliable. Although one might be inclined to the thought that the market is too small to merit adequate attention by engineering firms, it must be remembered that the atmospheric scientist is not trying to measure exotic properties of an unfamiliar atmosphere. The major problems are still related to the quantitative measurement of water, electrical conditions, and concentration of particulate matter in the air. In the early infinite variety and sophistication of instruments now available, there must be adequate and entirely satisfactory devices for measuring the fairly simple things that are required. Although the problem is

essentially and basically simple, there are innumerable pitfalls into which most investigators have fallen!

A meeting in Cambridge, early in 1959, sponsored by NSF, AMS, and FIER, served to introduce some of the problems to the instrumentation engineer. Not many tangible results have yet been seen from this conference, although hopes are still held that advances will be made. Good devices which help the experimental atmosphericist will be extremely reliable and marketable in many other fields.

But what of the civil engineer and his place in the field of the atmospheric sciences and particularly as related to experimental meteorology? Just as there is a challenging opportunity for the instrumentalist, the civil engineer will find opportunities to use the best of his or her ability. The projects needing attention range from the conservation of ponded water by evaporation reduction, the control of snow pack melt, preservation and utilization, to the development of more reliable sensing and monitoring devices for observing clouds, introducing suitable and optimum quantities of triggering materials into them for causing changes in clouds and cloud systems, and, if suitable reactions occur, having suitable ground facilities for coping with and handling the results. It is likely it will be a long time, if in fact it can ever be achieved, before the supply of atmospheric moisture can be tapped at will.

If this were possible, it is doubtful that it would solve many problems. The time when cloud-free regions may have greater value resource-wise than the best of clouds is not far away. Efficient utilization of solar energy is not far away and there is a strong possibility that techniques for dissipating clouds will be as useful as those for increasing their output efficiency.

The part of the civil engineer in the general field of weather engineering has not been adequately explored. Consider the importance of clean, pollution-free air to the well being and psychological attitude of the general population. A great mining engineer, the late Albert W. Johnston, founder of the Munitalp Foundation(26) which pioneered in the encouragement of cooperative research in experimental meteorology, believed that one day we would and should "mine" the atmosphere. Already the extraction and utilization of compressed and liquified atmospheric gases are important activities. Some day, and it may not be far away in time, portions of the atmosphere may be used as zones for carrying out useful synergistic reactions, utilizing drainage winds and other atmospheric motions for transporting the reacting materials from the reaction areas to the collecting zones. Fantastic? No more so than many techniques which today are commonplace and accepted routine activities.

The civil engineer has as great a stake in the hydrologic cycle as the meteorologist, the farmer, or the manufacturer. He would be smart if he became completely conversant with the fields of endeavor in atmospheric science, which he may have thought too basic for engineering attention. If this happens, everyone will benefit.

The greatest advances in technical achievement often may be directly related to war. Why not be intelligent enough to recognize that the only justifiable war is that against the elemental forces of hunger, ignorance, famine, drought, fear, and similar types of pestilence? If weather control is achieved, it is to be hoped that it will be directed toward the prevention or moderation of disastrous storms, unseasonal droughts, unwanted floods, and the gamut of other weather occurrences that cannot be put on the credit side of the climatic register. The economy of America, at least, has been adjusted to certain climatic normals or averages. Major departures from these conditions are of

serious consequence. If weather "control" can be used primarily toward smoothing out these excessive abnormalities, it would be of the utmost value. It is hoped that more than this will not be achieved. If one does not like the seasonal changes occurring in northeastern America, there are enough places having different conditions so that all but the most critical of individuals could find a climate to his or her liking.

The engineer, no matter what his interests and abilities, if imaginative, and if he has "the will to do," will find real satisfaction in coming to grips with the challenging, diverse, and difficult problems related to the atmospheric sciences.

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EXPERIMENTS ON TREATMENT OF SUMMER CUMULUS CLOUDS<sup>a</sup>

By Louis J. Battan<sup>1</sup> and A. Richard Kassander, Jr.<sup>2</sup>

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SYNOPSIS

During 1957 and 1958, the University of Arizona carried out a program of cloud-seeding research directed towards the study of the effects of silver-iodide nuclei on super-cooled orographic cumuli. Clouds over the Santa Catalina Mountains in southeastern Arizona were studied.

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DESIGN OF EXPERIMENT

The design of the seeding experiment was evolved with the assistance of K. A. Brownlee and W. Kruskal of the Department of Statistics, University of Chicago, Chicago, Ill. Briefly, the procedure involved an objective prediction, made prior to 0900 MST of each day, as to whether or not cumulus congestus or cumulonimbus clouds would form over the Santa Catalina Mountains. The main criterion for the prediction was whether or not the precipitable water at Tucson, Ariz. equalled or exceeded 1.10 in. When this occurred, the day was considered to be suitable for seeding, and an envelope was opened which

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August, 1959 Weather Modification Conference in Denver, Colo.

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specified which of two suitable days would be seeded. If more than one unsuitable day separated two suitable days, the first day of the pair was rejected and a new pair was started. The scheme of randomized pairs was adopted in order to take into account day-to-day correlations and to assure that there would be an equal number of seeded and not-seeded days.

The actual seeding was carried out with an Australian-type air-borne silver-iodide generator suspended under the wing of an airplane. The flight plan involved repeated passes at about the  $-6^{\circ}\text{C}$  level along a track upwind from the mountain range. The pilot normally started the generator at about 1230 MST and continued his flight until all the seeding material was exhausted or the burner went out. Normally the seeding period was of the order of 4 hr. The generator consumed a 20% solution of silver-iodide in acetone at a rate of 2 to  $2\frac{1}{2}$  gal per hr.

### OBSERVATIONS

In order to permit studies of cloud and precipitation processes the following observations were taken: (a) Visual cloud properties were recorded on a pair of carefully calibrated ground-located K-17 aerial cameras from which accurate estimates of cloud locations and dimensions could be made; (b) the location and spread of precipitation echoes were observed with a vertically scanning 3-cm radar set; (c) rainfall was noted with a network of 29 recording rain gauges; and (d) visual observations were made of the time and location of cloud-to-ground lightning strokes.

### RESULTS

The experiments conducted during the first 2 yr suggest that silver-iodide seeding caused some important changes in the natural cloud processes. During each summer sixteen pairs of days were studied.

*Rainfall.*—When data from both years were combined it was found that the mean rainfall per gauge was higher on the seeded days; however, the probability that the observed differences in the mean rainfall occurred by chance was quite high, about 0.14. This value was obtained from a sign-rank test which made use of a ranking of the differences of the mean rainfall of pairs of days. A comparison of the extreme rainfalls on seeded and non-seeded days showed greater differences, but the statistical confidence of a real difference was still not sufficiently high to be considered significant.

*Heights of Thunderstorms.*—An objective way to measure the relative frequencies of large thunderstorms is to take radar observations every 30 min and note whether there is at least one cloud extending above any particular altitude. When this was done, it was found that during the seeded days there were about twice as many echoes extending above 30,000 ft, 35,000 ft, and 40,000 ft. A sign-rank test in this instance showed that the probability that the differences in the number of clouds extending above 30,000 ft occurred by chance was 0.05.

*Lightning.*—Lightning observations were started in 1958. It was found that on the seeded days there were about nine times more lightning strokes than on the not-seeded days. A sign-rank test revealed that the probability of chance occurrence of the observed ranking of the differences of strokes on pairs of

days was about 0.015. It was interesting to find, that notwithstanding the large difference in lightning frequency, there was little or no difference in the number of lightning-caused forest fires. One might offer the explanation that the higher lightning frequency was offset by more rain which reduced the likelihood of the formation and spread of fires.

*Initiation of Precipitation.*—By means of the cloud camera and radar data, it was possible to note the vertical extent of clouds (and thus cloud-top tem-

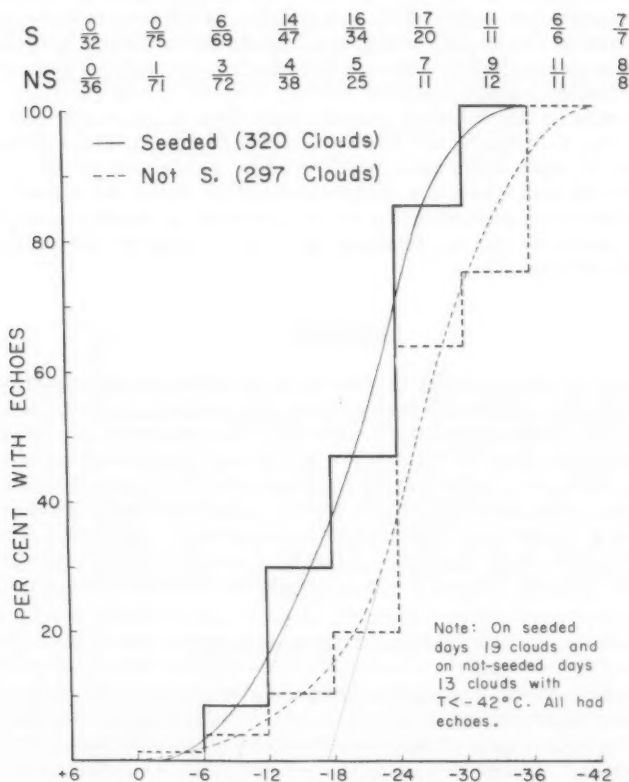


FIG. 1.—CLOUD TOP TEMPERATURE  $^{\circ}\text{C}$

peratures) and whether or not they contained precipitation. When a sufficient number of clouds have been examined it becomes possible to speak of the "probability of precipitation" in clouds whose summit temperatures are between  $-12^{\circ}\text{C}$  and  $-18^{\circ}\text{C}$ , or any other temperature interval. Fig. 1 shows a summary of the observations made during 1957 and 1958. Ten clouds, five in each sample, had temperatures above  $6^{\circ}\text{C}$  and were not plotted. The smoothed solid and dashed curves were drawn in by eye. It is quite obvious that on the

seeded days, the likelihood of precipitation was greater than on the non-seeded days. The fairly uniform shift of the curve towards the left lends support to the belief that the effect is real, and that in fact, the silver-iodide seeding caused the formation of precipitation in clouds which would not have precipitated naturally.

If the nearly straight parts of the curves are extended to the abscissa (dotted lines) it is found that the "not-seeded curve" intercepts the abscissa at about  $-17^{\circ}\text{C}$ . It might be argued that this result is reasonable because observations of ice-nuclei in the atmosphere show that in general, the concentrations at temperatures above  $-15^{\circ}\text{C}$  are small. As the temperature is reduced the concentration increases. It appears reasonable to assume that the dotted-dashed curve represents clouds in which the ice-crystal mechanism was effective in causing precipitation.

An extension of the "seeded curve" shows that it intercepts the abscissa at about  $-9^{\circ}\text{C}$ , a temperature just below the value at which silver-iodide crystals can be expected to become effective as ice-crystal nuclei.

If the interpretations of the significance of the dotted curves are correct, then one is led to the assertion that those precipitating clouds which fall to the left of the projected curves produced the precipitation by the condensation-coalescence process.

#### SUMMARY

In view of the fact that this research is still in progress, the writers feel that they are still not ready to draw final conclusions; that is, the foregoing has been a brief summary of some aspects of the research. Although the results to date point towards the conclusion that seeding produced important effects, it is vital that more data be compiled in order to be sure that the results have not been brought about by chance. This brief note has been written as a progress report for others working on similar problems. After more data are collected, it is hoped that some of the pressing questions in the important area of cloud-seeding can be given definite and unequivocal answers.

#### ACKNOWLEDGMENTS

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PHYSICAL STUDIES OF SANTA BARBARA STORMS<sup>a,b</sup>

By Theodore B. Smith<sup>1</sup>

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SYNOPSIS

The conduct and evaluation of cloud-seeding operations require weather observations on a geographic scale approximating the scale of motions producing the precipitation. Present (1960) observing networks are too sparse for an adequate study of the existing precipitation process. In order to understand the physical effects of seeding it is necessary to understand the natural mechanisms of precipitation formation and their variations. Several observing techniques for this purpose have been used during the Santa Barbara Project.

The physical measurements made during the Santa Barbara program include radar with PPI (horizontal) and RHI (vertical) scanning, atmospheric potential gradient, raindrop-size distributions, freezing nuclei concentrations, and assorted wind and temperature measurements. An additional valuable source of information has been radiosonde measurements of upper air temperature and humidity made every 12 hr at Santa Maria and Los Angeles. Combining this information into a coherent picture has made it possible to describe qualitatively a number of examples of natural mechanisms of precipitation formation. An excellent network of forty five recording raingages in Santa Barbara County is available for use in these studies.

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<sup>a</sup> Study supported by Advisory Committee on Weather Control, National Science Foundation, and California State Department of Water Resources.

<sup>b</sup> Presented at the August, 1959, Weather Modification Conference in Denver, Colo.

<sup>1</sup> Meteorology Research, Inc., Pasadena, Calif.

## INTRODUCTION

The advent of cloud seeding has created a need for weather observations on a geographic scale not routinely provided by the standard observational network. This applies equally to the problems of seeding operations and of evaluating possible seeding effects. In the case of summer convective activity, large precipitation cells may be several miles in diameter while the observing network is made up of stations 10 to 20 miles apart in dense areas but 50 to 100 or more miles separation is common. Under these conditions there is little opportunity for observing the systems of air motions which actually lead to the production of precipitation.

Winter storms are usually considered to be produced by air motions of the order of several hundred miles in horizontal extent. However, radar echoes from precipitation in such storms reveal considerable non-uniformity in horizontal structure. Precipitation occurs in sheets, bands or cells during these storms depending on air structure and terrain factors. Short distance variability in winter precipitation is particularly pronounced in orographic conditions when rainfall amounts may double or triple within a few miles.

In order to understand how cloud seeding works and how the natural precipitation process may be modified, it is necessary to understand the natural mechanisms of precipitation formation and their variations. This requires reducing the observations to a scale comparable with that of the precipitation process itself. Also required is a concentration of effort on the measurement of those parameters which will yield the most information about the operative precipitation mechanism. Methods for providing this information efficiently and economically have been under gradual evolution during the period from 1957 to 1959, in the Santa Barbara (Calif.) Project.

## SANTA BARBARA PROJECT

The Santa Barbara Project<sup>2</sup> is a cooperative program to investigate the results of cloud seeding in California winter storms. The project covers all of Santa Barbara County, and in 1958, also included Ventura County, which is adjacent to the southeast. An extensive recording raingage network was established and is maintained by the California State Department of Water Resources. The cloud seeding itself is carried out on a randomized basis with ground silver-iodide generators. The consultant makes a decision twice a day on meteorological grounds concerning the seeding potential during the ensuing 12-hr period. From those situations expected to be favorable for seeding, the Statistical Laboratory of the University of California at Berkeley selects, on a random basis, certain cases which can be seeded. The remaining cases are not seeded and are available for comparison with the seeded situations. The Statistical Laboratory later performs statistical analyses to determine whether significant differences exist between the seeded and unseeded cases. Physical studies are then made of each storm in an attempt to describe some of the details of the precipitation process and its variation from storm to storm. During these studies it is a tacit assumption that the possible effects of seeding will vary depending on the factors involved in the natural precipitation process itself. The chief reason for the studies is ultimately to delineate those storms,

<sup>2</sup> News and Notes; Bulletin, A.M.S., 1957, 38, p. 175.

or portions of storms, which may respond substantially to the seeding process from those situations which remain relatively unaffected.

Santa Barbara County is approximately 65 miles by 35 miles and, for this program, contains forty five recording raingages. Hourly rainfall amounts are thus available for all storms. Additional gages have been located in surrounding areas for comparative purposes. The principal comparison area is the Channel Islands about 25 to 30 miles to the south of Santa Barbara.

The principal terrain features of interest in the County are the east-west coast line and coastal plain, about 3 to 5 miles wide. North of the plain is the coastal ridge, about 4,000 ft high and extending east-west for about 45 miles. About 3 miles north of the ridge is the Santa Ynez Valley running nearly east-west with elevations ranging from around 1,500 ft to 700 ft. North of the Santa Ynez Valley the terrain becomes rough and unorganized with numerous 5,000 ft to 6000 ft peaks except in the northwest section of the County where the terrain is lower and more uniform.

### PHYSICAL MEASUREMENTS AT SANTA BARBARA

Observations made during the Santa Barbara program include radars with PPI (horizontal) and RHI (vertical) scanning, atmospheric potential gradient, raindrop-size distributions, freezing nuclei concentrations, and assorted wind and temperature measurements. Most of these observations were made from a United States Forest Service Lookout on La Cumbre Peak, at 4,000 ft on the coastal ridge about 6 miles north of Santa Barbara. The 3-cm radar was located on the roof of the lookout and had an uninterrupted view of precipitation approaching the coast from the south and southwest, but considerable ground clutter appeared from higher mountains to the north of the lookout. An additional source of valuable information comes from radiosonde measurements of upper air temperature and humidity made every 12 hr at Santa Maria and Los Angeles, California, from hourly airport weather data and from occasional pilot in-flight reports.

Perhaps the most powerful single source of information in these observations is the radar set. This has the ability of describing the structure of the precipitation over a very wide area in much greater detail than any other technique. However, there are practical limitations of the radar observations which must be kept in mind. An obvious possibility for use of the radar is the quantitative measurement of precipitation rates and an attempt to make direct observations of possible increases due to seeding. Considerable work<sup>3,4</sup> has been done on the quantitative measurement of precipitation by radar. The measurements are difficult and painstaking because of the need for accurate calibration of the radar equipment. In addition, correction must be made for attenuation of the radar signal due to rain intervening between the set and the area of interest. These problems together with the frequent non-uniformity in precipitation structure make it extremely doubtful that precipitation increases of the order of 10% to 15% could be detected directly by quantitative radar precipitation studies.

<sup>3</sup> Ill. State Water Survey; Final Rept. Contract DA-36-039 SC-64723, U.S. Army signal Research and Development Lab., March, 1958.

<sup>4</sup> Proc. 7th Weather Radar Conf., A.M.S., by L. F. Conover and H. W. Hiser, p. H-1, November, 1958.

There is one possibility for the direct detection of seeding effects by radar. This occurs in the case where conditions are marginal for the formation of natural precipitation and where seeding might trigger the precipitation process downwind from the generator while no precipitation was being observed elsewhere. A plume of precipitation would then be expected downwind, spreading out in the familiar manner of smoke diffusion from a point source. Such plumes have been reported on occasion by various radar observers.

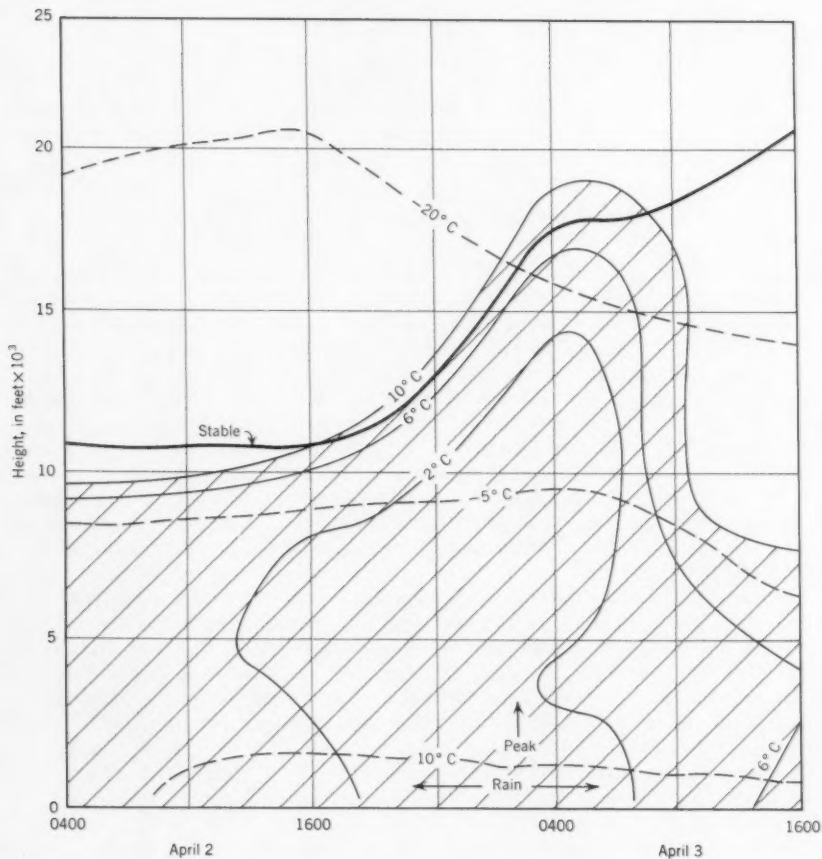


FIG. 1.—STRUCTURE OF STORM OF APRIL 2-3, 1958

The marginal conditions required for the appearance of these plumes exist in the Santa Barbara area fairly frequently. Under these conditions it should be possible to observe plumes from the two generators located on the Channel Islands as the precipitation forms downwind of the Islands and moves toward the coast. Unfortunately it was found that also, under these marginal conditions, the ridges on the Islands themselves could set off similar precipitation

plumes by causing the air to be lifted slightly during passage over the ridge. As a consequence, additional measurements are required to delineate the natural from the artificial plumes.

The use of radar in the Santa Barbara program has been confined to semi-quantitative studies of horizontal and vertical precipitation structure. Much can be learned from these studies concerning the type of air motion occurring in the precipitation process. Sheet or layer type precipitation structure is associated with slow, stable, relatively uniform upward motion. When the air becomes unstable, upward motions increase, the areas of upward vertical motion decrease in size and the precipitation structure becomes more cellular.

The methods for use of the radar data, and associated information to describe the details of the existing precipitation process, can best be indicated by consideration of a few storm examples.

*April 2-3, 1958.*—Fig. 1 shows a vertical-height-time cross section made from radiosonde data taken at successive 12-hr intervals at Santa Maria, California. Dashed lines represent air temperatures and solid lines represent moisture values plotted as the difference between temperature and dewpoint. The shaded area shows the moist-air region.

A characteristic feature of winter storms in this area is a low-level moist layer during the early portion of the storm. This layer is usually referred to as the marine layer and is topped by the "marine inversion," a region of warmer and drier air. Above the inversion the air is frequently dry except for possible layers of moist-air at high levels being advected into the area by the approaching storm. The top of the marine layer is shown in Fig. 1 as a heavy solid line with an indication that the air is stable at the top of the layer.

Rain began in the Santa Barbara area about 2000 PST on April 2. At this time the top of the marine layer as shown in Fig. 1 was about 11,000 ft at a temperature of  $-10^{\circ}\text{C}$ . Precipitation cells were seen on the radar to approach the coast from the southwest. Top of the precipitation was measured at 10,000 ft or about  $-7^{\circ}\text{C}$ . At 2029 an aircraft pilot reported the top of the clouds at 11,500 ft. According to freezing-nuclei measurements no natural nuclei could have operated to produce ice-crystal precipitation at the warm temperatures present in the observed cloud mass.

Raindrop-size distributions and atmospheric potential gradient were measured during this period and are shown in Figs. 3 and 4. The times of the thirty-one raindrop-size samples are shown in Fig. 4 along with the variations in potential gradient. As seen in Fig. 4 eleven samples were taken prior to 2000. The first nine of the samples are plotted as points in Fig. 3(a) together with a solid line which has been shown<sup>5</sup> to represent a generalized size distribution for raindrops produced by the coalescence or warm cloud process which does not involve the presence of any ice crystals. It is suggested by Fig. 3(a) that the first nine raindrop samples on April 2, were taken in coalescence-produced rain. Samples 10 and 11 (dashed lines) deviate markedly from the generalized coalescence distribution, and Fig. 3(b) shows that these samples correspond to the generalized size distribution found by Marshall-Palmer<sup>6</sup> (solid line in Fig. 3(b)). The conclusion is suggested that ice-crystal precipitation began abruptly at about 2000 PST.

<sup>5</sup> Proc. 7th Weather Radar Conf., A.M.S., by P. B. MacCready, T. B. Smith and C. J. Todd, p. A-17, November, 1958.

<sup>6</sup> J. Meteor., by J. S. Marshall and W. McK. Palmer, 5, 4, p. 165, 1948.

Further suggestive evidence for this change in precipitation mechanism is shown in Fig. 4 where an abrupt change to a negative potential gradient is observed beginning with samples 10 and 11. An increasingly popular theory of electric charge generation in clouds<sup>7</sup> associates the common formation of negative fields with the presence of ice crystal-produced precipitation.

These sources of information indicate that ice-crystal precipitation commenced at about 2000 PST on April 2. Since the ice-crystals could not have been formed within the cloud-mass below 11,500 ft, they presumably fell into

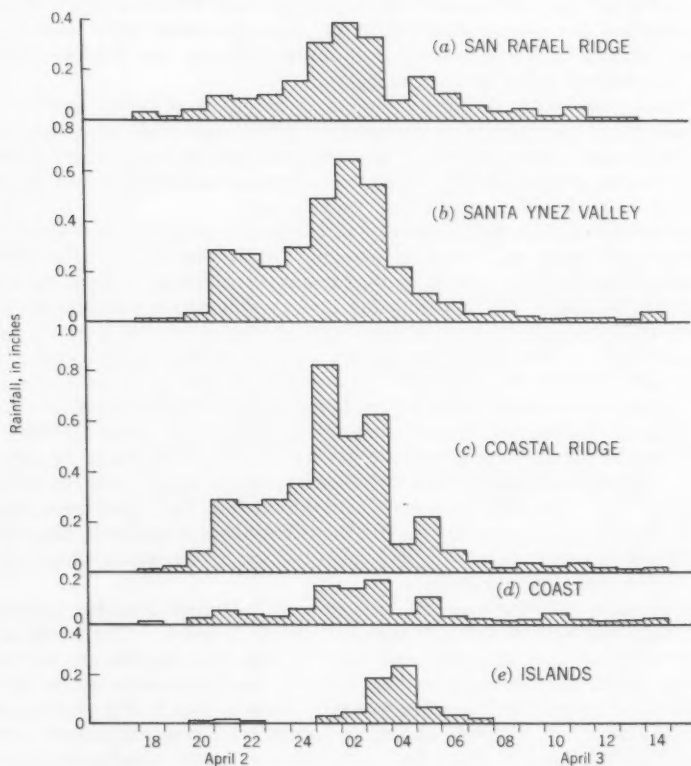


FIG. 2.—HOURLY RAINFALL AMOUNTS FOR STORM OF APRIL 2-3, 1958

the mass from a higher ice-cloud not seen by the radar or the radiosonde ascent. The patchy character of the precipitation indicates patchy non-uniform concentrations of ice-crystals falling from above. This mechanism of ice-crystal seeding from above is one of the most effective natural seeding processes observed.

The situation just described is an excellent example of marginal conditions for the formation of precipitation when occasional ice-crystals can release the

<sup>7</sup> Met. Monographs, by H. J. aufm Kampe, A.M.S., 3, 20, p. 270, July, 1957.

low-level moisture which would otherwise remain in the cloud. The patchy seeding in this example suggests that an opportunity exists, in this case, for artificial seeding to smooth out the irregularities in the precipitation process and make the precipitation more uniform.

After 2000 PST the top of the marine layer rose until at around 0100 PST on April 3, the radar top had increased to near 14,000 ft or about  $-15^{\circ}$  C. Peak

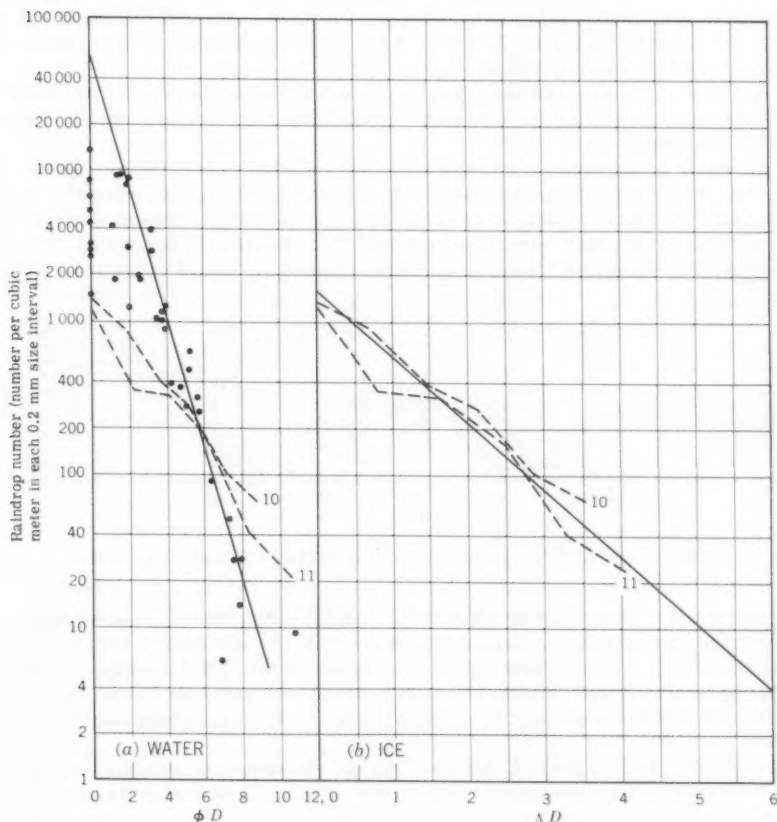


FIG. 3.—RAINDROP DISTRIBUTION, SAMPLES 10 AND 11, APRIL 2, 1958

participation occurred between 0100 and 0200, and by 0600 the precipitation had essentially ended. During the peak and later portions of the storm the depth of the marine layer had increased to where ice-crystal formation could take place within the cloud-mass below the marine layer top.

Horizontal radar cross sections through the storm showed a generally cellular structure, each cell being several miles in width. A summary of the storm would suggest that these cells developed within the marine layer, increasing in

height as the marine layer deepened, as suggested by the increasing heights of the radar echoes. Early in the storm ice-crystal seeding must have been accomplished from higher ice-cloud patches. Later in the storm ice-crystals could also have developed within the main cloud-mass itself.

Fig. 2 shows the hourly precipitation amounts for various portions of the Santa Barbara area. Each portion represents a nearly east-west line of recording stations beginning with the Islands and extending northward to the San Rafael Ridge. There is a distance of about 30 miles between the Island's line and the Coast, about 4 miles from the Coast to the Coastal Ridge, about 3 miles from the Coastal Ridge to the Santa Ynez Valley and about 5 miles from the Valley to the San Rafael Ridge.

Air flow at the precipitation levels is generally from the south or southwest during storm conditions so that these parallel lines are oriented nearly normal to the wind flow.

As would be expected under the unstable, cellular precipitation regime observed, the Coastal Ridge received the greatest precipitation amounts, since instability is usually released principally over the ridge. Due to these vertical motions total liquid water amounts tend to be highest in the clouds over the ridge, and ice-crystals falling from above collect the liquid water and cause it

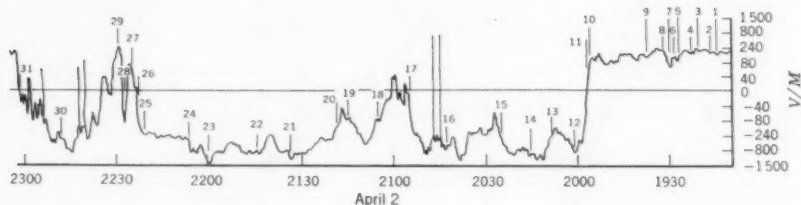


FIG. 4.—POTENTIAL GRADIENT FOR STORM ON APRIL 2, 1958

to precipitate. It is to be noted that the coastal plain did not receive particularly large amounts of rain during this storm. On the other hand, amounts were substantial in the Santa Ynez Valley, in the lee of the Coastal Ridge. This is undoubtedly the result of precipitation processes commenced over the ridge but not completed until the cloud-system had been moved downwind over the Valley.

*February 24-25, 1958.*—A different type of storm system is shown in Fig. 5. The principal characteristic of the storm is a low marine inversion (about 5,000 ft) throughout most of the storm. Considerable moist air was advected into the area at levels above the marine layer but there was no indication that ground level air passed upward beyond about 5,000 ft until very late in the storm.

Precipitation started in the Santa Barbara area about 2000 PST on February 24. At this time storm-moisture extended to 20,000 ft to 25,000 ft or to air temperatures below  $-20^{\circ}\text{C}$ . Under these conditions numerous ice-crystals would be formed naturally at high levels, fall toward the ground and collect whatever liquid water was present at the lower levels.

Tops of the radar echoes were generally around 13,000 ft to 14,000 ft early in the storm but increased to 17,000 ft to 18,000 ft during the peak rainfall period. An aircraft pilot reported layers of clouds to 23,000 ft (about  $-25^{\circ}\text{C}$ ) short-

ly after the precipitation had started. Horizontal radar cross sections indicated a relatively uniform precipitation structure sheets, bands, and occasional patches. From the structure of the precipitation and the great vertical depth of moisture during the storm it would be concluded that nature was doing a very extensive job of providing natural ice crystals. Whether additional artifici-

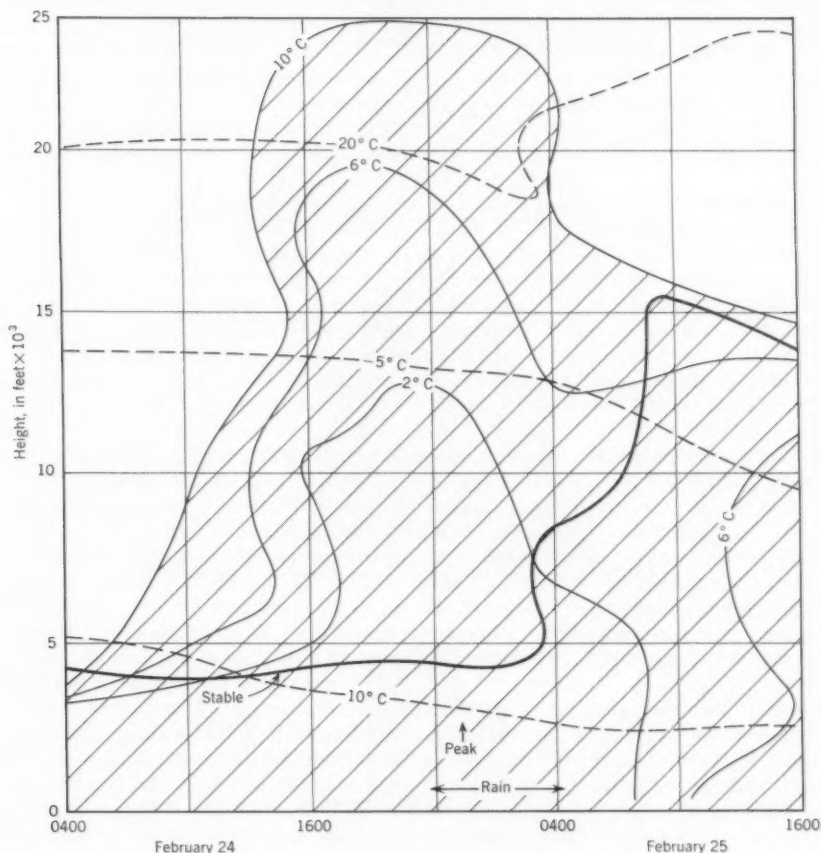


FIG. 5.—STRUCTURE OF STORM OF FEBRUARY 24-25, 1958

ally made ice-crystals would be beneficial under these conditions is an unknown factor in cloud seeding operations today.

Fig. 6 shows the hourly rainfall amounts for the storm of February 24-25. The striking feature of the chart is the extensive precipitation received by the coastal plain, only slightly less than occurred on the Coastal Ridge. Elsewhere the precipitation was relatively uniform and considerably less than observed near the coast.

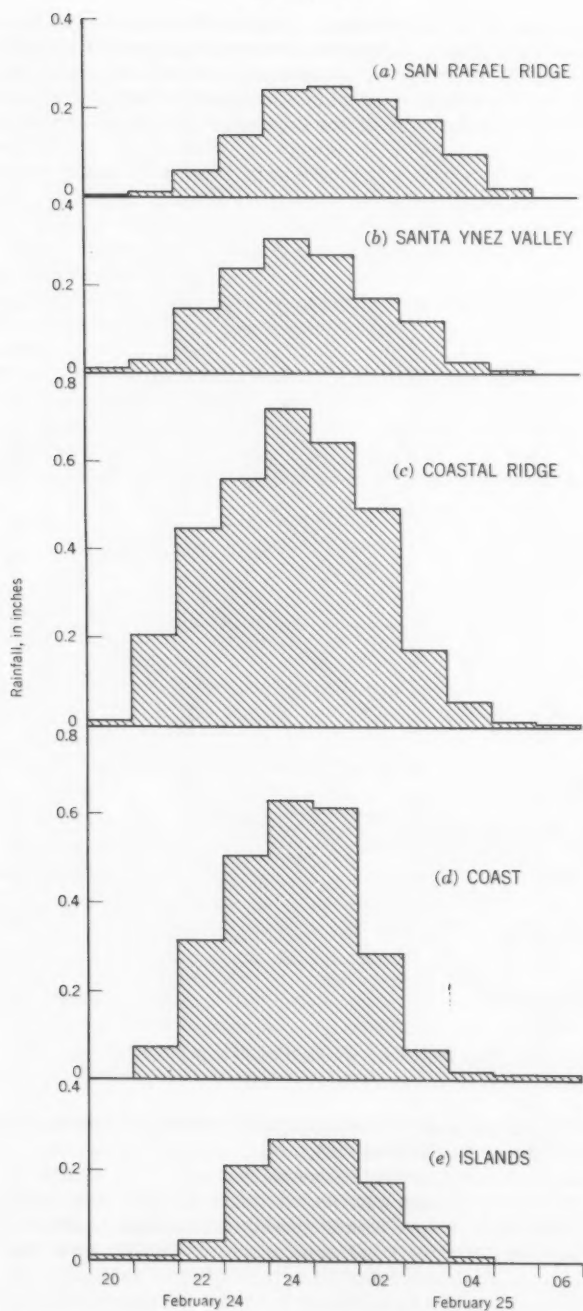


FIG. 6.—HOURLY RAINFALL AMOUNTS FOR STORM OF FEBRUARY 24-25, 1958

The explanation for this coastal maximum in precipitation has been given<sup>8</sup> by T. Bergeron. Under the stable, low level inversion conditions characteristic of the February 24-25 storm, surface air moving northward along the coast cannot flow over the east-west ridge north of Santa Barbara but is turned westward to pass through the Santa Barbara Channel. Winds at Santa Barbara under these conditions are moderately strong from the east with much higher velocities being occasionally reported by ships in the Channel. Frictional slowing down of the air by the coastal plain and convergence produced by the efforts of the air to flow around the Coastal Ridge combine to produce a piling up of air (and liquid water) in the immediate vicinity of the coast. As in the Feb. 24-25 case, ice crystals produced aloft may then collect this liquid water during their descent and substantially higher amounts of rain are produced in the coastal areas.

This phenomenon is essentially a low level one being produced by convergence in the layers near the surface. As seen in Fig. 6 the effects do not extend to the Santa Ynez Valley due to the stable, low inversion conditions prevailing. In view of these conditions and since moisture from the coastal source does not appear to influence the rainfall in the Valley it is considered probable that silver iodide released from ground generators would not rise to levels in the atmosphere where it could become effective in producing ice-crystals. Thus the storm of Feb. 24-25 was characterized by a large supply of natural ice-crystals and it is likely that it was relatively unaffected by artificial seeding.

*January 25-26, 1958.*—The storm of January 25-26, 1958 combines some of the features of the two preceding storms. As shown in Fig. 7 the characteristic marine layer was shallow early in the storm but deepened rapidly during the storm. Rain began at about 1300 PST when the top of the marine layer was only about 8,000 ft or 0° C. In agreement with the previous cases, natural production of ice-crystals could not have taken place in the marine layer by this stage in the storm. However, as in the February 24-25 example, advection of moisture into the area at high levels apparently produced numerous natural ice-crystals. This is indicated by a radar precipitation top of 19,000 ft shortly after the precipitation commenced.

The structure of the precipitation as viewed by the radar showed frequent bands and patches during the early part of the storm. Between 1930 and 2000 PST the character of the echoes changed rather abruptly from stratiform, layer type to cellular. This coincided with an increase in the top of the marine layer to about 11,000 ft and thereafter the top continued to rise. Thus after 2000, in terms of the depth of the marine layer, the January 25-26 storm then became similar to the April 2-3 example which also showed a cellular precipitation structure.

Fig. 8 shows the hourly precipitation amounts for the January 25-26 storm. The Coastal plain received substantial amounts of precipitation through 1900 but the precipitation rate decreased rapidly thereafter. The Coastal Ridge, however, did not receive its peak precipitation until the hour between 2000 and 2100. Since only about 4 miles separate the coastal stations from the ridge stations it is obvious that the coastal maximum precipitation and the coastal ridge maximum were produced by different processes. It is apparent that the precipitation characteristics of the January 25-26 storm are made up of the

<sup>8</sup> Tellus, by T. Bergeron, 1, 3, p. 15, 1949.

coastal maximum patterns described in the February 24-25 storm until 1900 followed by a change in precipitation regime to that characterizing the April 2-3 storm. Indicative of this change in regime is the change in radar echo characteristics from stratiform to cellular between 1900 and 2000 PST.

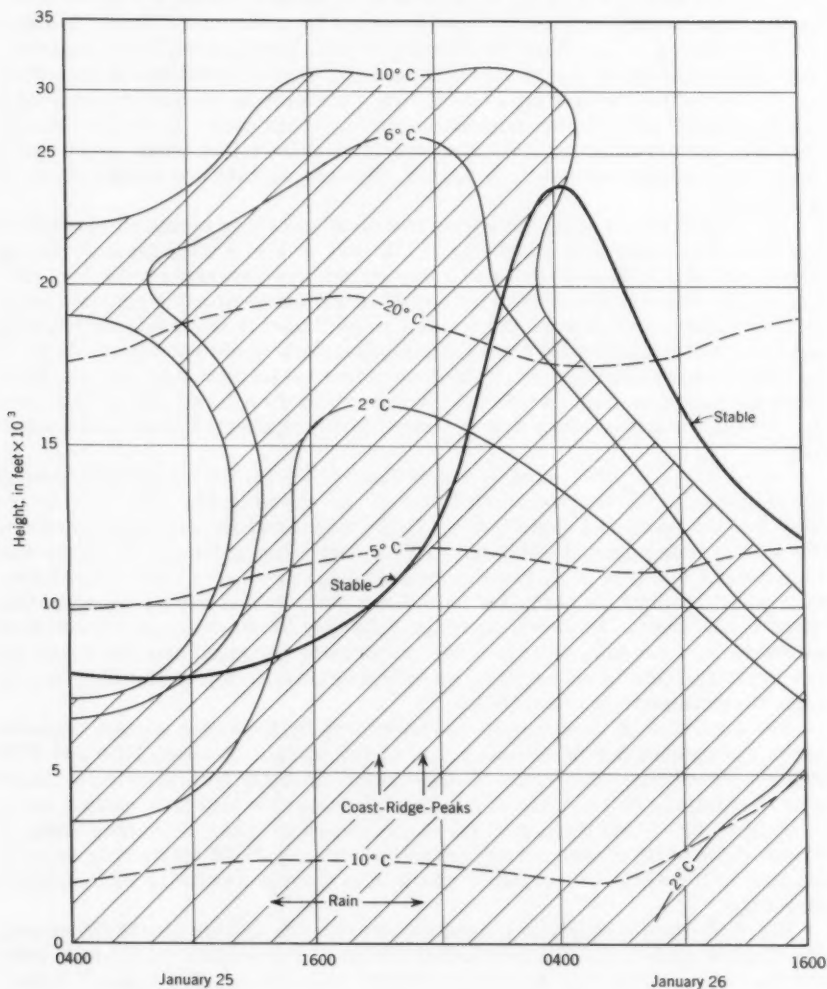


FIG. 7.—STRUCTURE OF STORM OF JANUARY 25-26, 1958

#### LOW-LEVEL CONTROL OF PRECIPITATION AMOUNTS

The variations indicated in area distribution of precipitation amounts from one storm to another have important general implications. It is indicated that low-level wind flow patterns exert an important influence on precipitation

amounts. In those areas where liquid water accumulates due to convergent flow, precipitation amounts increase if a releasing mechanism is provided. The latter usually consists of ice-crystals formed at high levels which fall

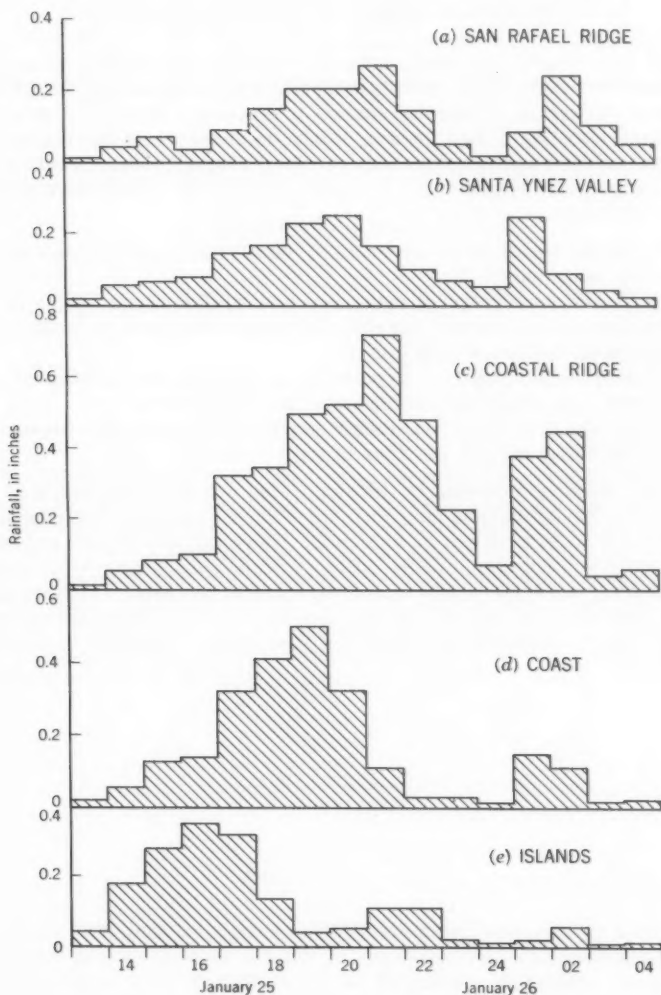


FIG. 8.—HOURLY RAINFALL AMOUNTS FOR STORM OF JANUARY 25-26, 1958

through and sweep out the lower level liquid water. Cloud seeding purports to influence mainly the releasing mechanism. To the extent that the low-level flow patterns control the actual precipitation amounts, increases in these amounts due to seeding will be difficult to detect. In some studies of cumulus

seeding, indications have been obtained of greater cloud growth during seeding. In this case, the seeding has directly influenced the low-level liquid water supply and the seeding effect will be more easily observed.

#### NEED FOR ADDITIONAL MEASUREMENTS

It has been shown that, using various rather easily obtained measurements, it is possible to reconstruct qualitatively many of the details of the precipitation processes occurring during the course of a storm. This is a step toward a better understanding of how seeding might influence these processes. Further progress requires additional measurements and the formation of better hypotheses on the possible action of the seeding. Some of the problems which require consideration are:

1. To obtain direct measurements of liquid water content or vertical motions within the clouds;
2. To obtain more frequent measurements of cloud tops during the storm;
3. To obtain a measure of the extent of natural ice seeding from high levels as a function of time during the storm;
4. To develop an improved hypothesis concerning the benefits of artificial seeding when numerous natural ice-crystals are present; and
5. To develop improved hypothesis concerning the relative importance and benefits of seeding various portions of the storm.

If cloud seeding continues to develop in the future it is likely that seeding operations will eventually be concentrated in those storms or portions of storms where maximum effects can be achieved. Development of new seeding techniques requires a knowledge of the optimum timing and location for introduction of the seeding material which is not available at present. Further progress toward these goals in winter storms will come from physical studies of the individual storm characteristics and the associated variations in precipitation mechanisms.

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SEEDING OF WEST COAST WINTER STORMS<sup>a</sup>

By Robert D. Elliott<sup>1</sup>

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SYNOPSIS

Weather modification has emerged as an important engineering application of the science of meteorology. This paper describes both the manually operated silver-iodide smoke generator and the remote-controlled generator operated by radio. The dispersal of silver-iodide smoke from ground generators was determined from analysis of seeded storm precipitation patterns as related to air mass, wind, and thermal structure supplemented by weather radar observations. The role of natural nuclear in the generation of precipitation and the effects of seeding on precipitation efficiency is considered. Finally, the economic effects of cloud seeding are evaluated.

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INTRODUCTION

During the past decade, weather modification has emerged as an important engineering application of the science of meteorology. The greatest impetus to its development was the basic work of Langmuir, Schaefer, Vonnegut and others in Schenectady, N. Y. The dry ice seeding of supercooled stratus clouds by Schaefer in 1946 provided the first clear-cut evidence that man could modify weather on a considerable scale.

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<sup>a</sup> Presented at the August 1959 Weather Modification Conference in Denver, Col.

<sup>1</sup> North Amer. Weather Consultants, Santa Barbara Munic. Airport, Goleta, Calif.

Today (1959) there are active in the United States several scientifically designed experimental projects being conducted for information-gathering purposes. There also exist about ten operational projects in mountainous areas which have been conducted almost continuously for anywhere from 5 yr to 10 yr. These latter projects are designed with the economic benefits of enhanced precipitation in mind. The goal is to maximize probable yield of precipitation and not necessarily to maximize the information on effectiveness, as would be the case in a scientific experiment. For instance, even a 10% increase in water supplies for hydroelectric generation could result in economic value one or even two orders of magnitude greater than the cost of the project. In this paper there will be discussed some of the methods and instrumentation used in these operational projects.

The basic principle of cloud seeding is to supply artificial ice-forming nuclei to suitable cloud forms in great numbers so as to make up the deficit of such nuclei in nature. The question as to what substances would serve effectively as artificial nuclei was answered by Langmuir, Schaefer, and Vonnegut.<sup>2</sup> They not only discovered several methods of nucleating clouds in the laboratory but demonstrated in the field that striking effects could be produced from such artificial nucleation.

#### THE SILVER IODIDE SMOKE GENERATOR

Attention will be confined to the generation of silver iodide smoke crystals, as this is the most commonly used artificial nucleant at present. A typical gas type silver iodide smoke generator, described in detail subsequently, emits about  $10^{15}$  crystals per sec. Only a small fraction of these will serve as effective ice-forming nuclei at the threshold temperature of  $-5^{\circ}\text{C}$ . At lower temperatures, the fraction of crystals which are effective increases rapidly. The source strength in effective crystals per second for various temperatures is shown in Table 1.

TABLE 1.—SILVER IODIDE SMOKE GENERATOR NUCLEI SOURCE STRENGTH<sup>a</sup>

Temperature (°C)	Number of effective nuclei per second
-30	$2 \times 10^{14}$
-25	$5 \times 10^{13}$
-20	$10^{13}$
-15	$2 \times 10^{12}$
-10	$10^{10}$
- 5	Threshold

<sup>a</sup> 1/10 gal per hr of 2% AgI in acetone solution.

The gas type silver iodide smoke generator is a modification and refinement of an original type, consisting essentially of a propane burner unit into which an acetone solution of silver iodide is sprayed. The theory of smoke-crystal generation requires the vaporization of the silver iodide followed by an immediate "quenching" or rapid cooling of the vapor. This produces immediate desposition (opposite of sublimation in the form of small ( $0.01 \mu$  to  $0.05 \mu$  range) smoke crystals. If the quenching is too slow, larger crystals and much smaller numbers of them are generated. As will be seen presently, it is important that there be large numbers of them.

A simplified schematic diagram of

<sup>2</sup> Final Report Project Cirrus, by the General Electric Research Lab. Part 1 - December 1953 - Report No. RL-1007. 1953.

the generator is shown in Fig. 1. Propane gas is taken off the propane tank through a pressure regulator, thence through a solenoid valve, which when open, allows full flow of the gas to a burner nozzle provided with a cylindrical shield to ensure the proper gas-air mixture and to protect the flame from drafts. The gas also passes into the silver iodide tank, pressurizing it and forcing the silver iodide solution through a needle valve on the spray head and thence into the flame.

Generally a 2% solution of silver iodide in acetone is used, sodium iodide being added in appropriate quantities to ensure dissolving of the silver iodide in the acetone. The typical burning rate of the solution is a tenth of a gallon an hour with a gas pressure of 5 psi. Use of concentrations of over 5% may lead to clogging. A burner unit design ensuring the proper degree of heat flow away from the nozzle is necessary to guard against the development of vapor

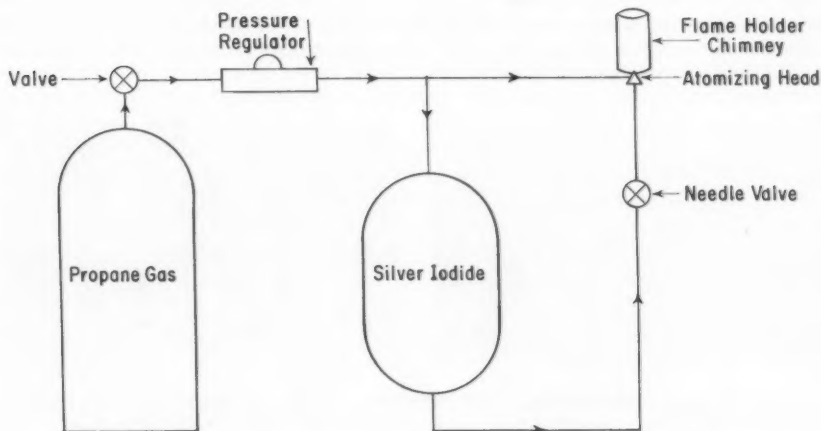


FIG. 1.—MANUALLY OPERATED SILVER IODIDE SMOKE GENERATOR

lock. Too rapid heat loss leads to precipitation of a crust of silver iodide on the burner head and subsequent clogging. These matters are extremely important for reliability of operation.

A much higher output can be achieved when a tube-type generator is mounted on an airplane in a position where the slip stream can supply an enormous flow of air through the burner unit and thus ensure adequate quenching with a high volume flow of fuel and reagents.

Pictures of generators are shown in Figs 2 and 3. The generator is shown with and without a wind screen in Fig. 2. The silver iodide solution tank is in the bottom section. Fig. 3 shows a generator mounted on a tower for use in country.

The generator output is calibrated by tests utilizing a cold box identical to a chest-type home freezer. While the generator is operating, a known volume of effluent is sampled with the aid of a small wind tunnel and injected, after suitable dilution, into the deep freeze. A supercooled cloud is formed by means of dropping a moistened pad to the bottom of the freezer or by simply blowing

one's breath into it. The silver iodide crystals injected into the supercooled cloud, serve as nuclei and grow by deposition, as in nature, until they become large enough to fall out on to glass slides, which are stacked one on top of another in the bottom of the deep freeze. The top slide, after a short period is removed and placed under the microscope and the number of ice crystals in the field of known size are counted. Then the procedure is repeated on successive slides until the number of crystals dropping out becomes negligible. Knowing the volume of the sample, the volume of the freezer, and the area of the field under the microscope, it is possible to arrive at an estimate of the crystal count of the output of the generator.<sup>3</sup>

In operating a network of such generators at ground level in mountainous terrain, it is desirable to place a number of them at remote high-altitude stations. In many cases this can be done by locating generator operators (normally a couple) in a mountain cabin where they are snowed in for the winter with contact being maintained by radio. This procedure introduces certain personal problems as a result of isolation by the heavy snow. Also, there is often no cabin near a desired site. For this reason, there exists a genuine need for a remote control generator.



FIG. 2.—SILVER IODIDE GENERATORS WITH AND WITHOUT WINDSCREEN



FIG. 3.—TOWER-MOUNTED GENERATOR AT HIGH-ELEVATION SITE

Although the basic concept of radio control of a gas-type generator has been well known for some time, the special requirements of this application led to many difficult problems. The principal requirements are: (1) reliability of operation, (2) resistance to the climatic rigor of exposure with extremethermal contrast in certain parts between on and off conditions, (3) positive information as to whether the equipment is operating or not, and (4) systems compatibility with available communications network.

In manual operations an operator is required to open the valve on the propane tank, ignite the flame emitted by the flame holder, and adjust the silver iodide needle valve to the point where the proper flow of solution is indicated on a flow-rate meter. In addition to this, he cleans the burner head, changes propane tanks, and refills the silver iodide solution tank as these operations become necessary. A further more important function of the operator, is to log the exact times of operation and to report any operational difficulties immediately.

<sup>3</sup> Final Report, Project Cirrus, by I. Langmuir, et al. 31. Dec. 1948, pp. 86-94.

The remote-control generator presently being used on several projects fulfills the functions of the human generator operator. Both the gas and liquid valves are actuated by means of a radio signal. A glo-coil, similarly actuated, ignites the gas in the burner unit. The atomizing head is carefully pre-set for the correct mixture. A time delay switch on the gas line operates at shut-off in such a way that the liquid in the line all burns out before the flame goes out. This successfully eliminates clogging from lack of cleaning. Oversize tanks provide adequate storage for a winter's supply of propane gas and silver iodide-acetone solution. A thermoswitch mounted on the flame-holder, when heated, initiates a radio signal which can be monitored to verify that the generator is operating. It also turns off the glo-coil after ignition. In the event that the flame is blown out by high winds, the thermoswitch, on cooling, initiates the reheating of the glo-coil to relight the generator. Finally, there is a running time meter which logs the actual flow of the silver iodide solution.

A detailed diagram is shown in Fig. 4. As the control switch (shown on the left side of the diagram) is closed by radio control, a potential exists between A and C which energizes all relays, the liquid valve, the running time meter, and the glo-coil filament transformer. When relay number 2 is energized, the gas valve, in turn, will also be energized, as a potential always exists between lines A and B.

With the gas valve energized (open) and the glo-coil filament transformer energized, the generator will ignite. After ignition, the normally closed thermoswitch opens, which in turn de-energizes the glo-coil filament transformer and relay number 3. When these contacts open, they produce an open contact signal back to the radio transmitter along lines D and E. This open line signal produces an alarm which is transmitted back to the control center, indicating that the generator is in operation.

To terminate the operation, the control switch is opened via radio contact. When this switch is opened, the running-time meter, liquid valve, and relays number 1 and 2 are de-energized. However, relay number 1 is a time-delay relay whose points will remain closed, keeping the gas valve energized for as long as 1 min after the control switch has been opened. This additional gas valve energization period allows the burning propane fuel to completely aspirate the liquid silver iodide solution from the burner head. The automatic generator cabinet itself contains a season's supply of 55 gal of 2% silver iodide solution. With a burning rate of 0.1 gal per hr, there is sufficient solution for 550 hr of operation. The 1,000 gal tank of propane is more than adequate even at the burning rate of 1 gal of propane per hr.

#### DISPERSAL OF SILVER IODIDE SMOKE FROM GENERATORS AT GROUND LEVEL

We shall now outline the gross features of the downwind dispersion of smoke from a ground generator and its eventual fallout in precipitation. This picture was derived from analyses of seeded storm precipitation patterns as related to air mass wind and thermal structure supplemented by weather radar observations.

Large scale tracer studies employing zinc and cadmium sulfide fluorescent particles, have been conducted in convectively unstable air by R. R. Braham,

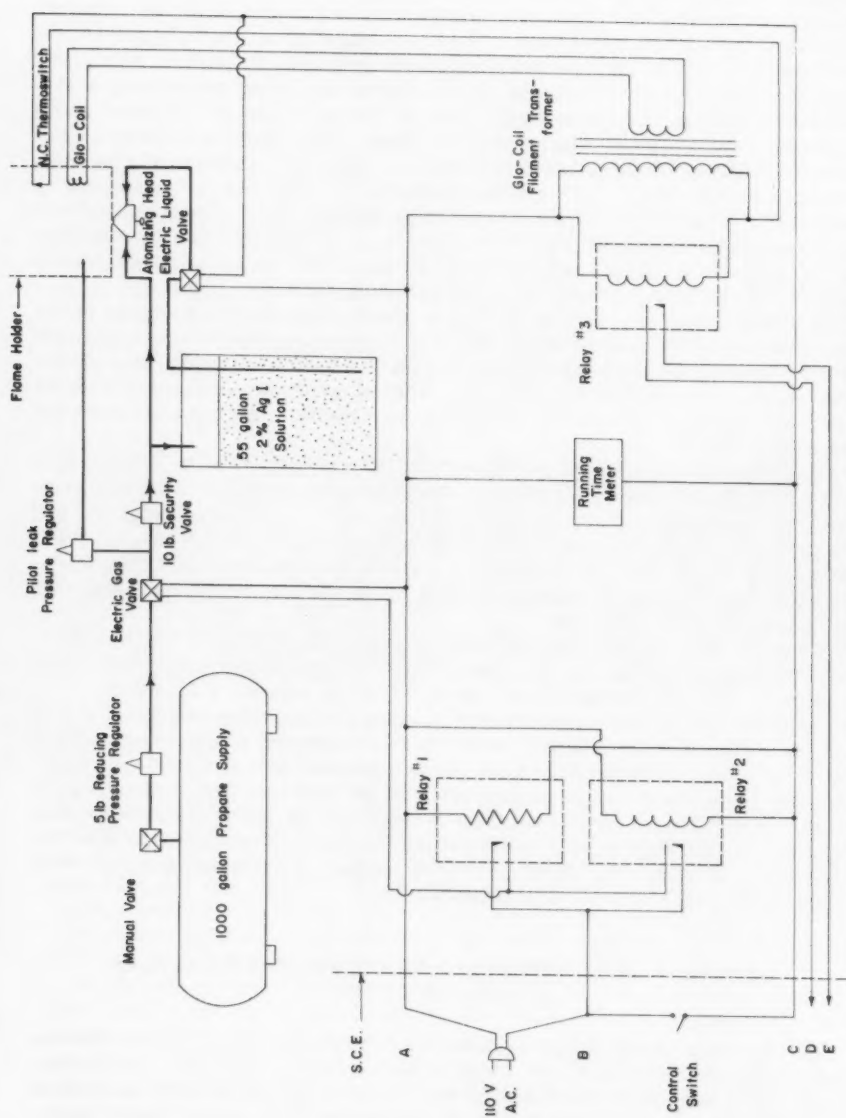


FIG. 4.—AUTOMATIC SILVER IODIDE SMOKE GENERATOR

B. R. Seely and W. D. Crozier<sup>4</sup> who found a Sutton-like horizontal spread of the plume but with dispersion through a deep layer, with a pattern showing spots of high concentration aloft. These spots are suggestive of what one might expect in traversing thermals or convection cells which had entrained the particles fanning out in a plume at low levels.

It seems clear that the plume first fans out under the influence of mechanical turbulence and mixes up to the gradient level, about 1,500 ft. Eventually, the plume is entrained into a convection cell. Convection cells contain updrafts

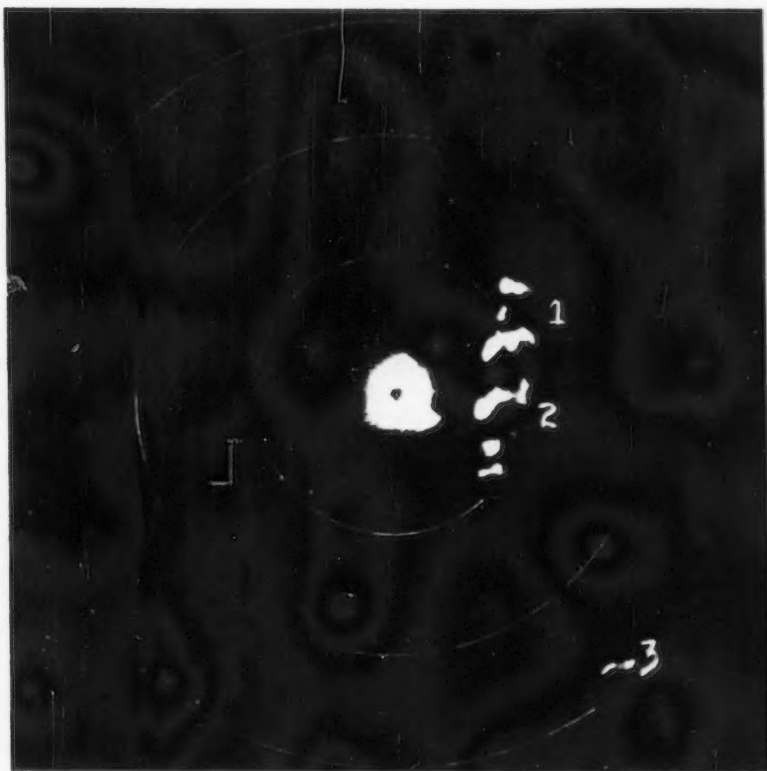


FIG. 5.—3 CM RADAR, PPI SCOPE, 10-MILE CIRCLES

of several meters per second and cover areas of a fraction to a number of square miles in area. They may occur embedded within a general cloud mass or may appear in isolated form as in a field of cumulus clouds. Radar evidence indicates a typical cell diameter under full instability conditions is 3 to 6 miles. There is a tendency for long lines of cells to appear oriented along the direction of the mean wind. Fig 5 shows a 3 cm Radar PPI scope picture of such a line

<sup>4</sup> "A Technique for Tagging and Tracing Air Parcels", by R.R. Braham, B.R. Seely, W. D. Crozier. Trans. A. G. U. Vol. 33, No. 6, 1952, pp. 825-833.

extending toward the north-northeast (along the mean wind). A silver iodide generator at 10 miles southeast was nucleating the cells and apparently producing a rather immediate effect as far as generating a radar echo is concerned. In this particular situation a single isolated line of cells appears. Under conditions of more widespread precipitation such lines may appear spaced 10 miles apart. Their point of origin seems to be determined by orographic features.

After entrainment, the smoke ascends in the updraft, or rather, perhaps, moves up stepwise in a series of updrafts or convection bubbles, until it eventually reaches a level where the temperature is low enough for effective nucleation to occur.

Following nucleation, there is a rapid growth by direct deposition of water vapor on the nuclei and resultant ice crystals. The precipitation size particles thus generated are of sufficient size to fall out. The average rate of fall-out from nucleation level is a matter of meters per second, the amount depending upon the size and shape of the precipitation particle and the strength of the updraft through which it falls.

Fig. 6 portrays in schematic form with typical dimensions the travel of the smoke plume released from a single silver iodide smoke generator located at ground level. The upper diagram shows, in plan view, the spreading of the smoke plume by mechanical turbulence in lower levels downwind from the source. The plume is indicated moving into the indraft region of a convection cell after travelling a distance of 9 miles. At this time it has spread to a width of 3 miles. The indraft zone of the cell is larger than the plume width so that all of the plume is entrained into the cell. Thereafter the smoke ascends in updrafts to the nucleation level. At the same time it drifts downwind within the cell in a direction about 40° to the right of the low-level drift.

As can be deduced from the data appearing in Table 1, a few crystals nucleate at the -5°C level, many more at the -10°C level (shown at 11,000 ft as typical of west coast winter storms) and still more at colder temperatures if the cloud top extends to higher levels. During and following nucleation the growing precipitation particles drift still farther downwind, with those which were nucleated first reaching the ground first. This is shown in the vertical cross section in the middle diagram of Fig. 6.

A great deal of variation from this pattern can result from differences in the distance from source to entrainment. This is a matter of the chance configuration of smoke plume and cells at a given time. In rugged terrain there are cell-breeding areas whose location under a given wind flow is dictated by orographic features. In these, the updraft motion is quasi-persistent at one place. A knowledge of such areas can be used to great advantage in reducing the travel time of the plume in low levels and thereby more accurately producing the desired effects at the target.

In addition, as might be expected, the downwind distance to maximum effect varies with the height of the freezing level and with the mean air flow. A very local and startling effect is observed when the seeding is done at a temperature near -5°C in supercooled fog.

From the foregoing, it appears clear that there is a limit to the control which can be exercised with this, or any other known dispersal system. This fact sets a lower limit on the size of the area which can be seeded. It has been deduced from considerations such as those above that an optimum ground generator network is an arrangement wherein lines of generators lie at approximately 5-mile intervals across the wind. Parallel lines spaced 20 to 30 miles downwind should

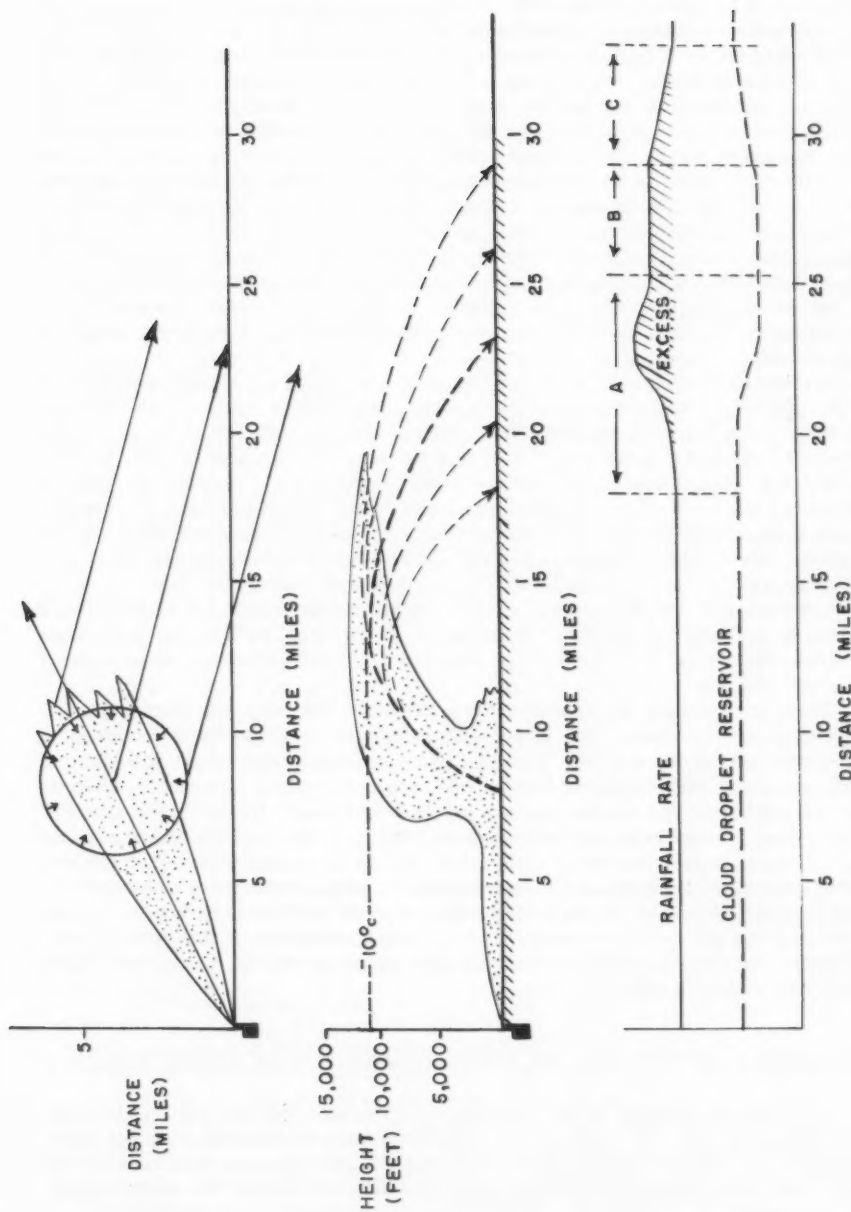


FIG. 6.—TYPICAL TRAVEL OF NUCLEATING SMOKE AFTER RELEASE FROM A GROUND-BASED GENERATOR

be added if required by the size of the target area. Because there exists a considerable drift, a factor depending on changing wind flow at different levels, there must be different networks for different types of storms and, indeed, it is necessary to change the operating network during the course of a given storm.

Mountainous terrain introduces complicating factors, other than the increase and fixation of convective activity. For example, it has been found that in addition to strong local channeling of the low level wind by canyons, there is a scale backing of the wind by about  $40^\circ$  when the air mass flow itself is normal to a mountain range. This extends to the elevation of the crest. Such a feature is seldom revealed in analyses based upon the conventional synoptic network.

In order to properly operate a generator network it is necessary to intelligently combine knowledge of local conditions with the conventional synoptic data received over the weather teletype. This requires considerable experience based upon special observations in the area of interest. This is the principal reason why it has become a custom to establish a resident meteorologist, experienced in cloud seeding, in or near the seeding target area to manage all operations.

Assuming that one can enhance the nuclei supply in a significant fashion, what concentration is desired at the nucleation level? A very simple estimate of this can be made on the basis that one would like to supply one nucleus for every 1,000 supercooled cloud droplets present. This would ensure a thousandfold growth in volume or, with spherical particles, a tenfold increase in diameter over that of the original cloud droplets. This would represent growth from a  $10\mu$  cloud droplet to a  $100\mu$  small precipitating particle of sufficient size to ensure rapid subsequent growth by the collision and coalescence process. Since there are approximately  $10^8$  cloud droplets per cu m, the required nuclei concentration is  $10^5$  per cu m. On this basis a minute's supply of smoke should serve to nucleate 1.2 cu km (0.29 cu miles) of cloud at  $-15^\circ\text{C}$ . The importance of ensuring the rapid dilution of the generator effluent through a large volume of cloud is obvious.

There are no man-made means (aside from the H-bomb) of achieving the required rapid dispersal of the smoke. Dispersal from a fast-flying airplane is orders of magnitude too low. It is therefore necessary to depend on the natural diffusion processes of the atmosphere to produce the required reduction in concentration before the smoke reaches levels cold enough for effective nucleation. Thus, smoke released from ground level or a low-flying plane is carried rapidly aloft in the very same updrafts in which the liquid cloud droplets are being generated most rapidly. This means that the smoke crystal concentration is much higher in the updrafts, and it is in the moisture-rich updrafts that most of them will serve as nuclei. Those which move on out of the updraft region into the environmental region will also serve as nuclei, but considerably later and with less effect.

#### THE ROLE OF NATURAL NUCLEI IN GENERATION OF PRECIPITATION

Thus far, no recognition has been given to the fact that the artificial nuclei are competing with natural nuclei during the course of the cloud seeding. Consideration of this factor will give more insight into the true requirement on artificial nuclei supply in order to make seeding worthwhile for precipitation enhancement.

What is the nature of the natural ice-forming nuclei supply? That supplied from the air mass is composed largely of small earth, dust, or sea salt parti-

cles. According to observations<sup>5, 6, 7</sup> there is a strong variation of nuclei content with temperature. In an average sample of air there seem to be about 10 nuclei per cu m effective at  $-15^{\circ}\text{C}$ ;  $5 \times 10^2$  at  $-20^{\circ}\text{C}$ , and  $2 \times 10^4$  at  $-25^{\circ}\text{C}$ . Compare these concentrations to the  $10^5$  per cu m proposed for complete nucleation by artificial nuclei. This temperature dependence means, in effect, that the higher (colder) the top of the cloud, the more efficient it will be as a precipitation producer because of the greater supply of effective ice-forming nuclei. Ordinarily, cloud tops at sub-freezing temperatures contain primarily supercooled liquid droplets because their temperatures are insufficiently low and there is a dearth of natural effective ice nuclei.

Precipitation is largely initiated through the deposition of water vapor on natural ice-forming nuclei which are supplied by the same convective updrafts that supply the water for cloud generation. The ice crystals generated by deposition upon natural nuclei, grow to snowflake size rapidly in the presence of supercooled water droplets because of their lower vapor pressure. That is, water is evaporated from the supercooled cloud droplets and diffused to the ice crystals. (Bergeron-Findeisen ice-crystal theory of rain formation). During descent the snowflakes collide with supercooled cloud droplets which freeze upon them. This riming process is an important mechanism in the growth of precipitation particles. Further down, after melting, the resultant raindrops collide and coalesce with cloud droplets, thus continuing their growth. The cloudy air is therefore scavenged by the precipitation particles which continue their growth until they fall from the base of the cloud.

The concentration of natural ice-forming nuclei effective at cloud top temperature, is generally too small to result in a downward flux of precipitation particles sufficient to completely remove the liquid water in cloud droplet form as fast as it is generated in the updraft. Therefore, a considerable fraction of the cloud droplets are transported by the stronger winds aloft upward and out of the cloud system and eventually evaporate.

A study of the water budget of a thunderstorm by R. R. Braham<sup>8</sup>, based on the numerous observations made in the University of Chicago thunderstorm project, showed that only 19% of the liquid water generated in a thunderstorm eventually reaches the ground as precipitation. The percentage for full-scale cyclonic storms is not known due to the almost complete absence of data on cloud water content. In a study of California winter storms R. D. Elliott<sup>9</sup> has computed, on the basis of a simplified theoretical model, that efficiencies of 50% to 75% can be expected.

In cases where the tops are warm, perhaps even above freezing, precipitation is still possible. This is the result of the growth of a few oversized cloud particles by collision and coalescence to the point where they have become precipitation particles. In summer cumulus this process may actually initiate

<sup>5</sup> "Ice-Crystal Counts and the Freezing of Water Drops", by E. K. Bigg. *Quart. J. Ry. Meteor. Soc.* Vol. 81, 1955, pp. 478-479.

<sup>6</sup> "Measurement of Natural Freezing Nuclei at High Altitudes," by E. J. Smith, A. R. Kassandra, and S. Twomey. *Nature* Vol. III, 1956, pp. 82-83.

<sup>7</sup> "Report on the Pasadena Cooperative Program of Ice Nuclei Measuring Techniques to the Advisory Committee on Weather Control", by P. B. MacCready, T. B. Smith, C. J. Todd, and K. M. Bessmer. *Pasadena, Meteor. Res. Inc.* 1956.

<sup>8</sup> "The Water & Energy Budgets of the thunderstorm and their relation to Thunderstorm Development," by R. R. Braham, Jr. *J. Meteor.* Vol. 9, 1952, pp. 227-242.

<sup>9</sup> "California Storm Characteristics and Weather Modification", by R. D. Elliott. *J. of Meteor.* Vol. 15, No. 6, 1958, pp. 486-493.

precipitation but the concentration of such oversize cloud droplets is relatively small outside of tropical ocean areas, and the supply therefore is inadequate in itself to assure a high efficiency.

Another source of freezing nuclei is the small ice crystals falling from cirrus clouds into tops of a cloud deck. This source is on the average small but may be important where streamers hang down from the cirrus level. Cirrus seeding must in these cases add to the efficiency of the storm system provided the induced precipitation reaches the ground without evaporating.

### ATMOSPHERIC MOTIONS

Ascending motion in the atmosphere is a necessary, although not a sufficient condition for precipitation. This implies, from continuity considerations, that the horizontal-motion field as well as the vertical field is involved. It is therefore pertinent to review the character of air motions and their role in cloud and precipitation generation.

Air motions important in one way or another in the precipitation process, range in scale from the 1,000-mile diameter counterclockwise (Northern Hemisphere) rotating whirl of air characteristic of a cyclonic storm system down to the 1 ft or even 1 in. diameter whirl of turbulent air motion. Vertical motions associated with the cyclone scale wind system are generally 2 to 10 cm per sec (0.07 to 0.33 ft per sec) and extend uniformly over a broad area of tens or hundreds of thousands of square miles. This motion is upward in the forward (eastern) portion of the system and downward in the rear (western) portion, and is associated with fronts. As the air is lifted to the condensation level, cloud droplets form upon condensation nuclei with precipitation eventually resulting, provided that the depth of lifting is sufficient for the nucleation and growth of precipitation size particles.

The precipitation from this type of motion is of low intensity, usually around a few hundredths of an inch an hour, and is steady and persistent. Higher rates of precipitation occur only where there exist much stronger upward motion. Such motion occurs with convective activity such as cumulus clouds where upward velocities may be 1 to 10 m per sec (3.3 to 33 ft per sec). Convection cells within a general storm also provide limited regions of high upward velocity and of high precipitation intensity. The existence of periods of moderate (0.11 to 0.30 in. per hr) or heavy ( $>0.3$  in. per hr) precipitation within a cyclonic storm system usually signals the presence of convective activity. The area covered by the convection scale updraft is measured in fractions up to several square miles.

Organized upward motion of a rather strong type also occurs where an air mass is blown up a mountain slope. This orographic lifting does not occur if the air mass is thermodynamically stable as the air then flows horizontally around the mountain. This means that if orographic upward motion is present there is almost certainly some convective activity present due to air mass instability.

Most air mass properties, such as moisture, heat, and suspended matter are diffused throughout the atmosphere by means of wind eddies on a scale of a few inches up to hundreds of feet in size. These air motions are, for instance, of great importance in the diffusion of artificial nucleants and of cloud particles in the atmosphere. They are most numerous where the wind shear is the greatest.

This occurs primarily at ground level, in and around convection cells, and at very high levels near the jet stream.

The role which the thermal instability of the air mass plays in generating a convection cell is illustrated in schematic form in Fig. 7. The series of four graphs shows the vertical-temperature distribution inside and outside of the cumulus cloud at various times during its growth. Some initial upward motion, such as that associated with a thermal bubble of warm air ascending from a hill or a hot spot on the ground, lifts the air to condensation level. Immediately there is a release of heat of condensation, which warms the cloud mass, making it buoyant. This heat continues to be released as the buoyant cloud accelerates upward and more condensation occurs.

The solid line (without entrainment) shows that as the cloud ascends it maintains a temperature warmer than the environment even though it grows cooler aloft due to adiabatic expansion as it encounters lower environmental pressure aloft.

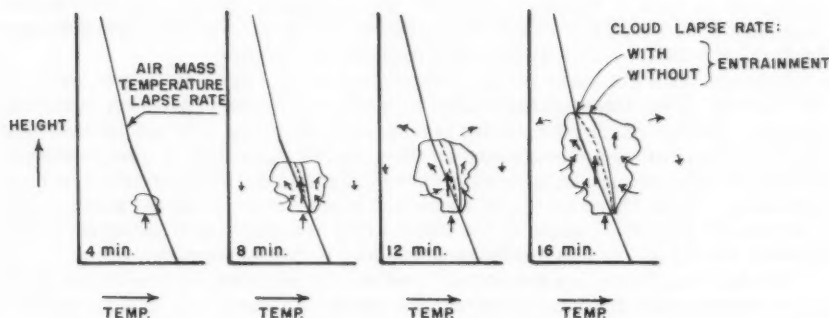


FIG. 7.—TYPICAL DEVELOPMENT OF A SMALL CUMULUS AND ASSOCIATED THERMAL AND WIND PATTERNS

Simultaneous with this process, the cloud enlarges itself through the entrainment of exterior air into its sides. This air is mixed by turbulence with the original cloudy air. The entrainment and mixing reduces the cloud air temperature as indicated by the dotted line in the diagram, but it is still warmer than the environment.

Eventually the cloud-temperature lapse curve crosses the environment curve as indicated in the last graph. The cloud will be cooler than the environment above this point and therefore the buoyancy becomes negative and its upward growth decelerates. If the air mass-temperature lapse curve had been steeper, to the extent that its temperature decreased more slowly aloft than that of the cloudy air, then no buoyancy would result from the condensation. The air mass would be termed "stable" and would be incapable of nurturing self-sustaining convective activity of this type.

The small arrows indicate the wind pattern in and around the cumulus cloud at various stages of its development. Note the strong updraft within the heart of the cell and the relatively weak downward motion in the exterior air mass. In a field of cumulus clouds continuity considerations require that in the absence of any cyclonic scale vertical motion, the ratio of the mean cell updraft

to the mean exterior downdraft be inversely proportional to the ratio of the updraft and downdraft areas. In a field of fair weather cumuli, the updraft motion will average about a hundred times the downward motion.

In the absence of precipitation, all of the cloud droplets generated in the updrafts are carried out of the sides and top of the cloud and completely evaporated in the exterior region of downward motion.

In a field of non-precipitating fair weather cumuli the life of an individual cumulus is 10 min to 20 min, as can be readily verified by direct observation. The unit of updraft is a single bubble or tower, a fraction of a mile in diameter. Although the cells are non-persistent units of motion with a seemingly random distribution timewise, a field of cumuli often takes on an orderly arrangement somewhat analogous in character to that of Benard cell motion under strong vertical shear. Orographic points in particular can generate long cloud streets in which the overall mean motion is that of a pair of roll vortices.

In an evolving situation where precipitation eventually occurs, a few favored cells develop at the expense of their neighbors. Thus, the whole character of the pattern changes with the cell spacing increasing as certain cells become enlarged. In such a region, a succession of bubbles operates to accumulate moisture within a larger cloud mass several miles in diameter and having a lifetime of hours. Such a situation is depicted in Fig. 8(a).

In an unstable air mass in the forward portion of a cyclonic storm system, the general upward motion is greater than the cell pattern external subsiding motion. Therefore, cloud droplets transported out of the cell updraft zone into the exterior area do not evaporate as they are not subjected to compressional heating in descent and, indeed, slow growth of additional cloud droplets may occur there. Thus, these cells are embedded in a general cloudy air mass, as illustrated in Fig. 8(b). Some of the taller cells are shown protruding above the general cloud top. In this region descent does occur between cells.

The fact that there is a net upward motion in the stratum of the general cloud mass requires the presence of wind convergence at low levels and divergence aloft, as indicated schematically by the heavy arrows on the left and right sides of Fig. 8. The convergence into the cell bases is delineated by the smaller arrows beneath the base of each cell.

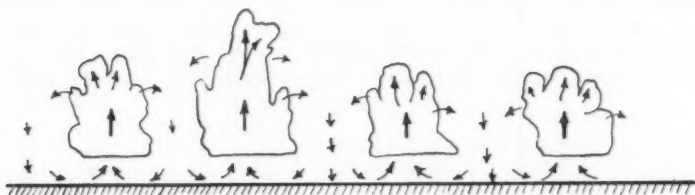
A cyclonic storm system contains various types of clouds. Fig. 9 depicts the basic features of a typical West Coast storm. The section is taken south of the storm center where there is no warm front. Fig. 9 is a vertical cross section oriented in an east-west direction and displays, in addition to cloud and precipitation types (not to scale), the principal cyclonic scale air motion relative to the front, which is itself advancing eastward. The height of the  $-10^{\circ}\text{C}$  level is shown as a dotted line. The principal region of cloud generation is where there is the strongest cyclonic scale upward motion and convection updrafts, that is, in the region between the front and 150 miles in advance of it. Therefore, the principal region of precipitation reaching the ground also lies here.

Cloud particles not transformed into precipitation particles in this area are either carried out of the tops and sides of the protruding convection cells and evaporated immediately, or they are carried out into the stable altostratus zone in the forward part of the storm. Here they may grow to precipitation size particles and fall out. However, in California winter storms most of this precipitation evaporates in the intermediate dry layer of air before reaching ground level.

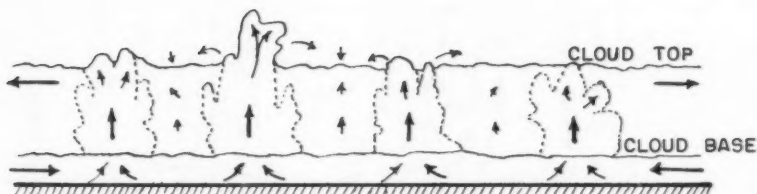
From this picture, it is clear that cloud seeding must be conducted continuously in the region between the front and 150 miles to the east thereof, that is, in the zone where instability is great. The extent of this instability zone, of course varies considerably with the type of storm.

#### SEEDING EFFECTS ON PRECIPITATION EFFICIENCY

A numerical estimate can be made of the relative effects of artificial and natural nuclei supply upon the efficiency of the precipitation mechanism, on the



(a) CONVECTION CELLS IN CLEAR AIR



(b) CONVECTION CELLS EMBEDDED IN CLOUD MASS

FIG. 8.—CONVECTIVE ACTIVITY

basis of a simple continuous convection cell model in which the ice crystal mechanism generates the precipitation. The basic assumptions and equations involved are presented elsewhere<sup>9</sup>.

Computed efficiencies (fraction of generated cloud water falling out as precipitation) are shown in Table 2. The background concentration figures are based upon average values already given. There is some day-to-day variation in these numbers, perhaps as a result of cosmic effects as well as of earth-bound variations in source strength associated with changes in low level wind direction. The artificial supply figures are based upon the Table 1 generator

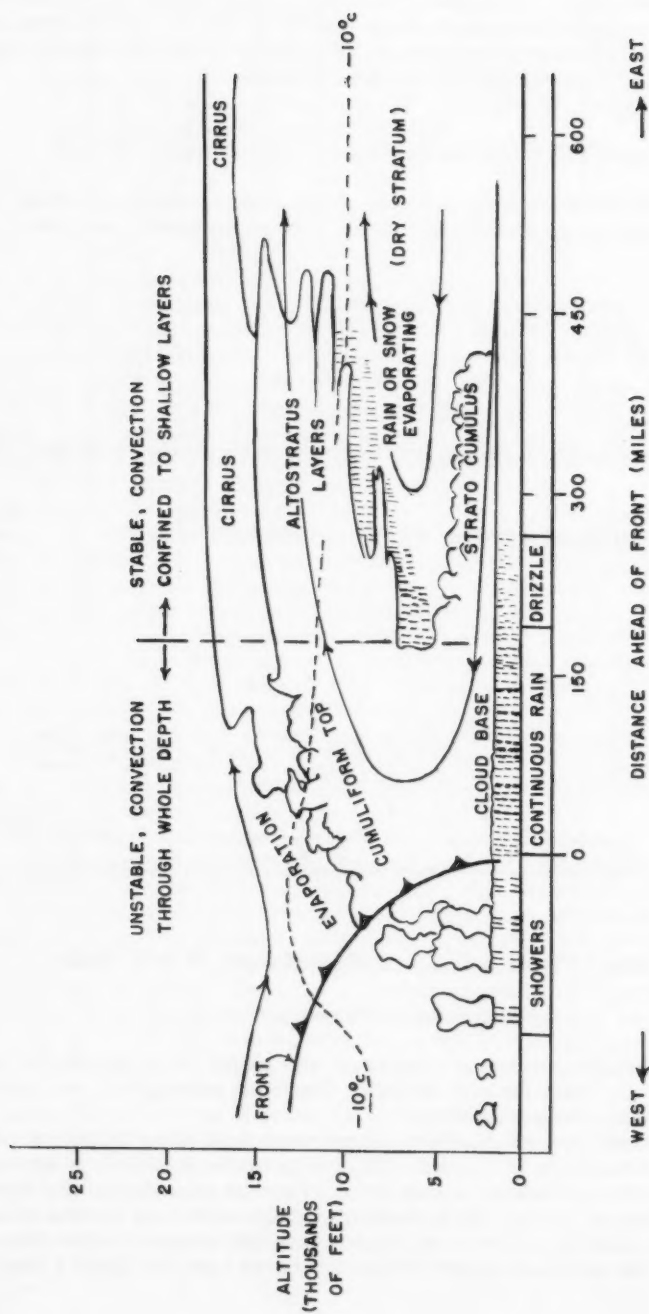


FIG. 9.—VERTICAL CROSS SECTION OF A CALIFORNIA WINTER STORM

source strength figures and the assumption of complete entrainment and turbulent mixing of the entire output of one generator within one typical organized convection cell of 26 km<sup>2</sup> (10 sq mi) cross section and a 2.5 m per sec (5.6 mph) mean upward motion. Two sets of computed efficiency figures are presented, one for straight convection with no entrainment, and the other for the case where the cell entrains and mixes cloudless but saturated exterior air quite rapidly as it ascends; so rapidly, in fact, that in the absence of precipitation, cloud water content would be 50% of that which would exist without mixing. The inclusion of this entrained air materially reduces the liquid water content of the cell (and therefore the precipitation rate) because there are fewer cloud droplets to collide and coalesce with the falling precipitation particles. No allowance is made for generation of rain by the all-water process, and therefore efficiencies for the warmer cloud tops may be unrealistically low.

According to Table 2, the increase in efficiency with seeding is quite striking except where cloud top temperatures are exceptionally low. The table sug-

TABLE 2.—SEEDING OF A SINGLE CONVECTION CELL WITHOUT ENTRAINMENT AND WITH 50% MIXING.

Item	Temperature at Top of Convection Cell				
	-10°	-15°	-20°	-25°	-30°
Natural background nuclei concentration, in crystals per cubic meters	$2 \times 10^{-1}$	$10^1$	$5 \times 10^2$	$2 \times 10^4$	$10^6$
Artificial nuclei concentration, in crystals per cubic meters	$1.5 \times 10^2$	$3 \times 10^4$	$1.5 \times 10^5$	$0.8 \times 10^6$	$4 \times 10^6$
Natural precipitation efficiency	0	0.13	0.53	0.84	0.96
Artificial precipitation efficiency	0.50	0.85	0.91	0.96	0.97
Natural precipitation efficiency with 50% mixing	0.0	0.0	0.42	0.81	0.93
Artificial precipitation with 50% mixing	0.36	0.82	0.90	0.93	0.94

gests that the more nuclei supplied the better, and that the type of supply employed in this computation is adequate to produce a marked effect, except in clouds whose tops reach -30°C. One also notes that a supply exceeding 10<sup>6</sup> per cubic meters would be wasteful of artificial nuclei. The dispersal system should be designed to provide a more rapid diffusion if concentrations exceeding this occur in the nucleation zone.

Any manageable form of supplying artificial nuclei cannot depend upon penetrating say, the base of each cell, as it develops, by airplane or other aerial means, and seeding just that cell during its lifetime. This can be done, of course, for special purposes, such as in hail suppression, where an extra heavy supply of nuclei are needed in certain identifiable dangerous cells. However, in winter storms, the cells cannot be located visually and one wishes, moreover, to supply nuclei to a large number of such cells simultaneously or at least nearly simultaneously. Accordingly, the silver iodide smoke is most often distributed from a network of ground generators.

In warm-front situations where the natural precipitation is generated in a slow rise over a frontal surface, the smoke would have to be injected above the

frontal surface. However, natural rates of precipitation are quite low in such a situation and economic value of the seeding is questionable. On the other hand, if convective activity occurs above the warm front surface, then aerial seeding could be of value.

The foregoing estimates of the effect of nuclei supply on efficiency are based on a continuous process. Actually, a transient phase occurs when the seeding first takes effect. There is an immediate reduction in the reservoir of liquid cloud droplets held within the volume swept out by the newly created precipitation particles. This reduction of the cloud droplet reservoir in itself results in a reduction in subsequent precipitation rate because there are fewer cloud droplets available to be scoured out. However, the enhanced nuclei supply far overshadows this effect and there is a net increase in efficiency of the system.

The lower diagram in Fig. 6 indicates, schematically, the changes in rate of precipitation and in extent of the reservoir of cloud droplets. In Zone A the reservoir is drawn down, with a simultaneous large increase in the precipitation rate. Thereafter, a quasi-equilibrium is established between the enhanced nuclei supply and the reduced reservoir level leading to a lesser, but still enhanced, precipitation rate as shown in Zone B. Finally, in Zone C, as the nuclei are used up, the reservoir is restored and the effect tapers off. For typical dimensions, orientations and movements, the convection cell, which moves relative to the surface plume, is over and entraining the plume for about 25 min. This limits the amount of smoke entrained in any one cell. The clear-cut breakdown into zones is idealized for clarity.

In addition to the direct effects of cloud seeding resulting from the artificial stimulation of the precipitation process, the artificial nucleation itself has an effect upon the storm air motions. Thus, it has been established by observations carried on at the University of Arizona<sup>10</sup> that, as predicted by theory, seeding enhances updrafts and raises the cloud top level appreciably. The release of heat of sublimation at a much lower level than that which occurs with natural nucleation results in added buoyancy forces, and accordingly increased updrafts with enhanced generation of liquid droplets. This, in turn, leads to a new release of heat of condensation. This process has been termed "double release" by T. Bergeron<sup>11</sup>.

### ECONOMIC BENEFITS OF CLOUD SEEDING

A brief resume of methods for evaluating the effects of seeding to increase precipitation is recounted at this point. It can be said, in general, that one must predict what would have happened had there been no seeding, then compare this to what was observed to occur during seeding. Now the state of the art of quantitative precipitation prediction is much too primitive to permit prediction of basin-wide precipitation accurately enough to reveal a seeding-produced 10% or 20% change in precipitation. Fortunately, one can "hindcast" with considerably more accuracy what the precipitation would have been in the target area in the absence of seeding on the basis of what was observed to occur in some

<sup>10</sup> "Design and Execution of a Program of Randomized Seeding of Orographic Cumulus", by L. J. Battan, A. R. Kassander, Jr. Paper presented at 163rd National Meeting of American Meteorological Society. 1958.

<sup>11</sup> "The Problem of Artificial Control of Rainfall on the Globe," by T. Bergeron. *Tellus*, Vol. 1, No. 1, pp. 32-43 part 2, *Ibid.*, Vol. 1, No. 3, 1949, pp. 15-32.

nearby unaffected "control area." The historical precipitation records are used to establish a regression equation relating the storm, monthly, or seasonal precipitation in the target area to that in the control area. On the basis of the scatter of points about this regression, one can establish an error of estimate. Using these tools, one then determines the significance of an observed precipitation excess. Even though hindcasting is much more accurate than forecasting, the error of estimate is still sufficiently great that the probability of a chance occurrence of an excess of 10% or 20% is considerable. However, the greater the number of such excesses, the smaller the probability of their being merely a chance occurrence and therefore the greater the significance of the results. Regression Analyses of long-term projects have been published by R. D. Elliott and R. F. Strickler<sup>12</sup> and by the Advisory Committee on Weather Control<sup>13</sup>.

Because the weather runs in cycles (that is, there is a serial correlation between years), with a high frequency of a certain type of weather continuing for a year or two, to be followed by high frequency of another type thereafter, it is possible to obtain spuriously high or low results in a given year through the use of the historical regression technique. J. Neyman<sup>14</sup> has indicated that for scientific testing this effect can be overcome by using a randomized seeding schedule wherein some of the seedable storms, randomly selected, are not seeded but reserved for comparison with seeded storms. Questionable precipitation records also add to the problem of using historical regressions. With randomization, a network of newly established rain-gages can be used, thus reducing still further the error of estimate.

The Advisory Committee on Weather Control, on the basis of their statistical analysis of numerous cloud seeding projects, have concluded that in western mountain watersheds, seeding projects have increased precipitation by 10% to 15%. From time to time reports appear of much higher increases, generally in connection with the seeding of summer convective clouds. Because of large summertime variability of precipitation, evaluation of seeding effects by means of the statistical target-control area precipitation comparison regression technique is difficult, and there remains considerable doubt about these values. Yet it is tempting to accept them as real since the very low natural efficiency of summer convective activity makes possible, in theory at least, a greater increase in precipitation through artificial nucleation than would be the case with winter storms. It is interesting to note that 10% to 15% increases are considered economically beneficial, over and above the seeding costs, and therefore this makes the seeding of one of nature's more efficient precipitation mechanisms profitable.

A 10% increase in snowpack and in consequent runoff may result in as much as an additional 100,000 acre ft of water available for storage, from a watershed target area of 1500 sq miles. The value of this water for hydroelectric generation of electricity may range from \$3 to \$20 per acre-ft, depending largely on the head. The value is considerably less if the watershed is not fully developed or if water has to be spilled at peak flow.

<sup>12</sup> "Analysis of Results of a Group of Cloud Seeding Projects in Pacific Slope Watershed Areas", by R. D. Elliott and R. F. Strickler. Bulletin Am. Meteor. Soc. Vol. 35, No. 4, 1954, pp. 171-179.

<sup>13</sup> Final Report of the Advisory Committee On Weather Control, Vol. 1. 1957.

<sup>14</sup> Chapter III "Weather Modification in California", by J. Neyman. Bulletin No. 16, State Water Resources Board, State of California. 1954.

R. R. Reynolds and E. P. Warren<sup>15</sup> analyzed the economic value of cloud seeding increases to a typical California irrigation district covering 190,000 acres and found that a 10% precipitation increase in the watershed supplying the district could be worth \$1,125,000. They also computed the value of such an increase to a marginal dry farming area, such as the western Great Plains, and found it could increase farm value by 51%.

The cost of cloud seeding geared to the cited applications is on the order of \$20,000 or \$30,000. It is clear therefore, that the value exceeds the cost by several orders of magnitude. This explains to a great degree the sustained interest and participation in many cloud-seeding projects even though it is not possible, with present observational data and statistical techniques, to obtain scientifically definitive results in any given place even over a period of several years. It is a matter of taking a calculated risk. The mathematics of decision-making in applying weather modification has been covered by G. D. Berndt.<sup>16</sup>

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<sup>15</sup> "Cloud Seeding - A Problem of National Importance", by R. R. Reynolds, N. D. Sturm, E. P. Warren. Paper presented at 1952 Summer Meeting of Institute of Mathematical Statistics at Michigan State College. 1954.

<sup>16</sup> "An Evaluation of Commercial Cloud Seeding Operations Conducted During the Summer Months in South Dakota", by G. D. Berndt. Vol. II Final Report of the Advisory Committee on Weather Control. 1957.

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SEEDING OF CLOUDS IN TROPICAL CLIMATES<sup>a</sup>

By Wallace E. Howell<sup>1</sup>

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SYNOPSIS

A synopsis of cloud-seeding experiments shows substantial agreement among experimenters that seeding with spray or hygroscopic particles often dissipates small warm clouds but often stimulates convective activity and initiates or increases rainfall from clouds that exceed approximately 4000 ft in depth, increasing precipitation by 50% or more. On the other hand, seeding with dry ice or silver iodide for effect in super-cooled clouds appears to produce a smaller but still considerable precipitation increase. While open to questions of interpretation, the results suggest strongly that present seeding techniques can produce important local rainfall increases at many places and times when water deficits cause loss and hardship.

The result of the warm-cloud seedings accords well with currently accepted theories of precipitation formation in tropical clouds, while the result of the cold-cloud seedings does not. A new model of convective cloud fields is proposed that would describe the approach of individual clouds to the rain stage in terms of the accumulated growth of rudimentary precipitation particles that, when it exceeds some critical limit, results in precipitation which, in turn, stimulates activity in the first cloud to reach this stage and suppresses it in other nearby clouds. Warm-cloud seeding affects the model directly by increasing the supply of rudimentary precipitation particles; silver-iodide seeding does so indirectly by increasing both the rate of growth of rudimentary pre-

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August, 1959 Weather Modification Conference in Denver, Colo.

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precipitation particles and the volume of cloud in which they may grow, thus acting upon the coalescence process rather than through the sublimation process.

## INTRODUCTION

The tropical climatic belt includes the greatest deserts on earth and other wide expanses where a rainy season more or less adequate for agriculture and other major water uses alternates with a marked dry season. It is furthermore a region where the adequacy of the water supply must be measured against generally high evaporation rates. Only a small portion of the tropics, mostly the less habitable lands, receive at all seasons an adequate rainfall.

Most human enterprises in the tropics that depend on water, primarily agriculture and stock raising and to a lesser extent hydroelectric and manufacturing enterprises, lead a rather precarious existence, suffering frequently from drought and, less frequently, from surfeit of water. Even a small measure of control exerted to alleviate the severity of these natural climatic defects would be of immense value and improve the lots of vast numbers of people. It is natural, therefore, that the prospect that modern discoveries in cloud physics may lead to some measure of control over rainfall has received widespread attention.

It is now more than 10 yr since experiments were begun in the tropics with the purpose of testing cloud-seeding techniques, and nearly 10 yr since these experiments have been followed into the field by commercial applications of these techniques. In 1954 a study under the auspices of the World Meteorological Organization<sup>(1)2</sup> reached the tentative conclusion that artificial increases in rainfall, while they might be of economic importance, would probably be under 10% of the natural rainfall and very difficult to detect, and randomized tests were proposed. However, no general review of weather-control activities in the tropics has appeared since then.

Two natural mechanisms that convert clouds to rain have been recognized, one operating through the coalescence of small cloud droplets to produce larger ones and eventually raindrops and usually referred to as the warm rain or coalescence rain process, and the other operating through the sublimation on ice nuclei of water vapor evaporated from supercooled water droplets, generally referred to as the Bergeron-Findeisen process or the sublimation process. The material that follows will consider first the seedings intended to stimulate coalescence rain, second those intended to stimulate the sublimation process, and third a comparison of the results of these experiments with the theories of rain formation and suggestions for further theoretical work.

## SUMMARY OF EXPERIENCES

*Warm-cloud seeding.*—Table 1 lists the principal experiments that have been reported on the seeding of warm clouds for the purpose of stimulating rain by the coalescence process. It is not an exhaustive list, but it contains all those for which quantitative data have been reported in the literature.

The experiment in Honduras was an outgrowth of the drop-breaking chain reaction theory of Irving Langmuir.<sup>(18)</sup> On a day during the dry season, the

<sup>2</sup> Numerals in parentheses, thus (1), refer to corresponding items in the bibliography.

top of a cumulus cloud was seeded with water in a coarse spray. Subsequently the cloud grew rapidly to be a large shower that gave a heavy rainfall most unusual for that season of the year, no other rain occurring nearby.

The experiments by the East African Meteorological Department comprise a series of trials undertaken at various places in Tanganyika, Kenya, and Uganda during the rainy season or the period immediately preceding it when cumulus clouds reached considerable size with reasonable frequency. Initial experiments with silver iodide in 1951 had had a negative outcome, but experiments

TABLE 1.—INSTANCES OF WARM-CLOUD SEEDING IN THE TROPICS

Date	Locality	Responsible agency	Reference
1948	Honduras	General Electric Co.	2
1948	Philippine Islands	Philippine Weather Bureau	3
1948-49	Hawaiian Islands	Pineapple Research Institute and Hawaiian Sugar Planters' Association	4
1952-56	British East Africa	East African Meteorological Department	5,6,7,8,9
1952-53	Hawaiian Islands	Territorial Cattleman's Council, Pineapple Research Institute and Hawaiian Sugar Planters' Association	10
1953-54	Ocean waters near Puerto Rico	Cloud Physics Project, University of Chicago	11
1953-55	Madagascar	Service Meteorologique, Madagascar	12
1954	Cuba	W. E. Howell Associates	13
1954	Pakistan	Pakistan Meteorological Department and U.N. Technical Assistance Programme	14
1954-55	French Equatorial Africa	Meteorological Service of the A.E.F.	15
1955	Hong Kong	Hong Kong Royal Observatory	16
1957-58	India	National Physical Laboratory of India	17

were continued from January through April 1952 by seeding in cycles of 3 days, the first day with silver iodide, the second day with salt bombs carried by balloons into the clouds, and the third day left unseeded. Again the days of silver-iodide seeding showed no increase in rainfall as compared with the unseeded days, but on days of salt seeding the rainfall 6 to 12 miles downwind from the release point was substantially greater. Rainfall at the release point, upwind from the target, was apparently lighter on seeded than unseeded days. Experiments of the same nature, but omitting the silver-iodide seeding, were conducted in 1953, 1954, and 1956, the 1953 seeding of 64 cumulus resulting in rain on 37 occasions and in very light rain or virga on 10 additional occasions. The time between seeding and appearance of rain ranged from 7 min to 35 min,

averaging 22 min. In 1954 the seeded days selected at random gave considerably higher rainfall than unseeded days, 24 out of 33 seeded clouds giving rain. In 1956 the seeding was done by firing rockets into selected clouds which, upon bursting, dispersed finely ground salt. A rain-gauge network was installed in and around the target watershed, and upon determination that a day was considered suitable for seeding, a decision was taken at random whether to seed or not to seed. Thirty rocket firings on 7 seeded days gave rain from every cloud seeded; heavy following 11 firings, moderate following 14, and light following 3. The times between seeding and rain ranged from 3 min to 37 min, averaging 11 min before heavy rain, 15 min before moderate, and 6-1/2 min before light rains. On 70% of all occasions rain appeared within 8 min. The rainfall pattern of the 7 seeded days as compared with that of 6 seedable unseeded days showed a shift of the maximum from the upwind rim of the watershed (which sloped downward in a direction of the wind) to a point 2 to 5 miles downwind from the firing site near the downwind edge of the target, along with a considerable intensification of the maximum. The experimenters were led to conclude as follows:

"Seeding of suitable clouds nearly always induces precipitation but it is difficult to be sure that the seeded cloud would not have rained naturally. In the present series of experiments, it appears fairly certain that practically all the seeded clouds rained earlier and more heavily than they would have done naturally and that cloud seeding is a practical method of increasing rainfall over a specified area. In many cases the observations and results strongly supported the view that the seeded clouds would not have rained naturally."

The trials in the Philippine and Hawaiian Islands in 1948-49 were inspired by the 1947 reports of dry-ice seeding in the United States, and on these occasions mostly warm clouds were seeded with dry ice, any effect in them being attributed to the mechanical influence of the dry-ice pellets in sweeping out cloud droplets and releasing them as larger particles. In the Philippines, the one cloud seeded yielded precipitation shortly afterward and appeared to take on an increased rate of development. In Hawaii, 54 seeding tests on 15 days yielded rain or virga 20 times, generally in less than 16 min after seeding. Both heavier rainfall and a higher frequency of rainfall were observed on seeded days, and the heaviest rains seemed to be associated with sub-freezing cloud tops. Cloud thickness was distinguished as the most significant factor in determining whether the seeding would produce rain.

Tests in the Hawaiian Islands were resumed in 1952-53. Non-freezing clouds, generally small in size, were seeded with a spray of sea water or salt solution. Precipitation echoes were subsequently observed by radar on 9 out of 30 occasions, the time between seeding and the appearance of an echo being typically 11 min, with rain after 20 min. The experimenters attributed the small proportion of successful seedings to the small size of the clouds.

The observations made in 1953 and 1954 by the Cloud Physics Project of the University of Chicago (Chicago, Ill.) comprise, by far, the most extensive effort yet undertaken to measure the physical parameters associated with cloud development and precipitation and to obtain an objective measure of the efficacy of warm-cloud seeding. Since all seedings in the tropics were carried out over the open sea, in cumulus whose physical characteristics differ markedly from those over land, (19,20) the results are perhaps not directly comparable with those of other experimenters. All cloud seedings were done with coarse water

spray, at first at the rate of 130 gal per mile (small valve), later at the rate of 400 gal in 18 sec (large valve), released 3,000 ft to 5,000 ft above the cloud base. Clouds were selected by the flight controller in pairs as nearly similar as possible, and a decision was made at random, unknown to him, as to which one of the pair would be seeded. Both clouds were subsequently traversed and studied, the initiation of precipitation being observed by radar. Table 2 shows the results in the form of contingency tables.(11) Each unit in the table stands for a pair of clouds, the number 4 in the first section, for example, meaning that there were 4 pairs of clouds in which each of which the treated cloud produced an echo and the untreated cloud produced none.

It was concluded that the small-valve treatment was ineffective in initiating rain, but that the large-valve treatment appeared to increase the average probability of rain from 4% to 44% and to be significant at a level of 5% if the results from two periods of experimentation may be validly combined. In the treated

TABLE 2.—CONTINGENCY TABLE FOR RADAR ECHOES  
FROM TROPICAL CUMULUS

		Treated cloud of pair		
		Echo	No echo	Total
Small valve				
Untreated cloud of pair	Echo	3	4	7
	No echo	3	22	25
	Total	6	26	32
Large valve				
Untreated cloud of pair	Echo	5	6	11
	No echo	17	18	35
	Total	22	24	46

clouds, rain was detected in from 2 min to 16 min after the seeding, averaging  $8\frac{1}{2}$  min for the small-valve and  $6\frac{1}{2}$  min for the large-valve treatments, compared with echoes beginning in from 2 min to 26 min in the unseeded clouds for an average of 12 min. It was then concluded that treatment produced a significantly shorter time-lapse before initiation of rain. There was an increased tendency, especially for the large-valve treatments, to give echoes below the level of the plane rather than above.

In the Madagascar experiments, finely powdered salt was dispersed in the clouds at a rate of from 10 to 100 cc per km by blowing heated air up through a can of ground salt. Clouds were seeded on 101 days scattered over 22 targets. The results were analyzed principally by comparison of rainfall in target gauges with their climatic averages. Eight positive, 8 indifferent, and 4 negative outcomes were reported. The clouds themselves were not methodically observed, though it was reported that no effect of seeding was seen unless the clouds were more than 3,300 ft thick. The experimenters concluded that the results were "encouraging" but not at all clear-cut.

The Pakistan experiments were carried out in a region of the upper Punjab where the wind during the monsoon season is either westerly and dry or southeasterly and showery. Powdered salt was dispersed during southeasterly winds

at a rate of about 10 g per sec into the air near the ground by a heater-bellows device so that some of it would be carried by convective currents into clouds forming downwind. Seeding was done in two areas, one mountainous and one more plain. The results were analyzed by establishing from a previous 40-yr period the normal relationship between rainfall in the 50° sector downwind from the seeding sites and neighboring sectors on either side, and comparing this ratio for the seeded year with this normal. In one area the ratio in the seeded year was the highest on record and  $2\frac{1}{2}$  times the normal; in the other area, it was the second highest on record and about 80% above normal. Most of the apparently stimulated rainfall fell at a considerable distance, 80 km to 100 km, from the seeding site.

The experiments in Cuba in 1954 were undertaken in the winter dry season to evaluate the possibility of accomplishing stimulation at that season in warm clouds over the level plains of southern Camaguey Province. Typical clouds were cumulus with bases 4,000 ft to 5,000 ft above sea level, their tops penetrating into the dry subsiding air aloft whenever they exceeded a few thousand feet in thickness. Seeding was done with water spray in fine droplets released within the lowest few hundred feet of the cloud, in updrafts whenever possible. Three clouds, between 800 ft and 2,300 ft thick, each dissipated about 15 min after seeding. One other, 3,500 ft thick, darkened and bulged at the base immediately after seeding, but did not rain. A cloud 4,800 ft thick gave a light shower that began 11 min after seeding and lasted 30 min. Six seedings in clouds more than 7,000 ft thick were all followed by heavy rain beginning from 11 min to 25 min after seeding (average 16 min) that lasted 40 min or more. Isohyetal maps for the period of the experiments showed an unusually heavy concentration of rain in the seeded zone.

The experiments in French Equatorial Africa were conducted over selected agricultural areas by seeding some clouds with water spray in quantities of about 200 l per run, and other clouds with 20-g ampoules of finely powdered salt. Seedings of both stratocumulus and cumulus clouds were done. Observations of the results were far from complete, since only 27 seedings out of 42 resulted in observations of rain or no rain and if rain how long after the seeding it commenced. For 11 cases of stratocumulus seeding, rain ensued three times, commencing an average of 17 min after the seeding from cloud layers ranging from 1,200 ft to 2,000 ft in thickness. Rain failed to fall from seeded stratocumulus layers ranging from 500 ft to 2,000 ft in thickness, the thinnest layer being dissipated in the seeded area. Out of 16 seedings of cumulus clouds for which the observations were complete, 9 were followed by rain commencing from 3 min to 17 min (average time  $8\frac{1}{2}$  min) after seeding, from clouds ranging from 2,000 ft to 6,000 ft in thickness and averaging 5,000 ft thick. For the 7 cases when rain failed to ensue, the thickness ranged from 2,000 ft to 4,000 ft, average 2,700 ft. All seeded cumulus thicker than 4,000 ft yielded rain. On three occasions, salt seeding was carried out in cumulus clouds connected with a pre-existing shower, and extension of the rain area in the direction of seeding, cross-wind and upwind, was observed. From these data and from qualitative observations of similar clouds in the vicinity of the seedings, the experimenters were led to the following conclusions:

- "(1)—It is possible to provoke rain artificially in French Equatorial Africa, even in dry periods, from warm clouds. (2)—The rain can be

obtained from either cumulus or stratocumulus clouds seeded with either salt or water. (3)—It is likewise possible to provoke the extension upwind or crosswind of natural showers under certain geographical conditions."

In May 1955, some experiments were made at Hong Kong by spraying water from nozzles placed on hilltops where the spray would be entrained into the bases of clouds. The records from a network of rain gauges failed to indicate any effect of the seeding.

In India, basic physical and climatic studies were begun in the early 1950's looking toward the methodical study of rainfall stimulation techniques,(21) culminating in experiments during the monsoon months of July through September in the 1957 and 1958 seasons near Delhi. Seeding was done from a fixed location on the ground by spraying a salt solution into the air at a rate of about 1 gal per min. After it was determined that a particular day was seedable, a decision was made as to whether to seed or not, based on previously sealed random numbers. For analysis, the results of each year were divided into two groups, those days with winds from the southeasterly sector and those with northwesterly winds, and the mean ratio of rainfalls in the upwind and downwind sectors for seeded days were compared with those for unseeded days. Three of the four groups showed substantially heavier rain in the downwind area when seeded, and the fourth very slightly less rain. The experimenters were led to conclude that

"the three cases of positive results would seem to suggest an appreciable proportionate increase of rain in the target sector and, if this could be taken as due to seeding, the results would have to be treated as significant. Considering, however, the various uncertainties of the method followed, and also that, despite randomization, effective balancing of similar meteorological situations between two sets of days, 'seeded' and 'not seeded', may not be secured by trials during one season, it is hardly possible to come to any conclusion until the trials have been repeated for a number of seasons."

Warm-cloud seedings with salt have also been carried out commercially in Puerto Rico, Hispaniola, Cuba, and the Philippine Islands, but the results are not cited herein because they add nothing and are mostly confused by simultaneous silver-iodide seeding.

Because of the wide variety of climates under which the several experiments were conducted, direct comparison between them is of doubtful meaning. However, the majority of experimenters agree on many points; that seeding of shallow clouds resulted in their dissipation without yielding rain that reached the ground; that seeding of clouds of about 3,000 ft to 4,000 ft thickness was followed by light to moderate showers falling from them much more frequently than from comparable unseeded clouds; that nearly all clouds thicker than about 4,000 ft yielded rain subsequent to seeding that was often moderate to heavy, with noticeably greater frequency and heavier amount than for comparable unseeded clouds; and that where comparisons of rainfall amount were made, these indicated an increase due to seeding that probably exceeded 50% of the natural rainfall.

The times recorded between seeding and the onset of rain are likewise difficult to compare, especially since the longest time recorded by each observer depended to some extent on his patience or on his opinion as to the connection between the seeding and the subsequent rain. However, there may be a real

difference between the rather short gestation times of 7 min or 8 min associated with the release of salt or massive water spray in the middle levels of the clouds and the longer times of about 15 min associated with spray introduced near the cloud base.

*Seeding of supercooled clouds.*—The principal experiments on the seeding of clouds with dry ice or silver iodide for the purpose of stimulating precipitation by the sublimation process are listed in Table 3. Like Table 1, it is not exhaustive. From among some 25 commercial projects that have yielded evaluation data, it lists only those representing a second or subsequent period of operation that has been evaluated in substantial accord with "rules of the game"

TABLE 3.—INSTANCES OF COLD CLOUD-SEEDING IN THE TROPICS

Date	Locality	Responsible agency	Reference
1947	Atlantic near Florida, U.S.A.	General Electric Co.	22
—			
1949-59	Mexico	Mexican Light and Power Co.	23
1951	Belgian Congo	Meteorological Service Belgian Congo	24
1951	Bolivia	Meteorological Service Bolivia	25
—			
1951-54	Taiwan	Rain Stimulation Research Institute	26
—			
1951-52	British East Africa	Meteorological Service	5,6
1953-59	Peru	W. E. Howell Associates	27,28,29,30
—			
1953-59	Cuba	W. E. Howell Associates	31 to 35
—			
1954-55	Belgian Congo	Meteorological Service Belgian Congo	36,37,38
—			
1956-57	Florida, U.S.A.	Advisory Committee on Weather Control	39
1955	Cuba	W. E. Howell Associates	40
1955	Puerto Rico	W. E. Howell Associates	41
1957	Cuba	W. E. Howell Associates	42
—			
1957-58	Arizona, U.S.A.	Institute of Atmospheric Physics, University of Arizona	43

established previous to the operation, in connection with the initial operating season.

The first cloud seeding in the tropics was undertaken by a research group in the course of an exploratory flight into a hurricane cloud system. A super-cooled layer of stratiform-cloud was seeded with dry ice at the rate of less than 1 lb per mile along a 100-mile path, and on return along the path about 300 sq miles of cloud were observed to have been modified. Cumuliform clouds, however, were not observably affected even by two doses of 50 lb of dry ice in each of two large cumulus heads. The hurricane swerved suddenly from its previous course at the time of the seeding, though it is questionable whether the two events were related.

In the mountainous region between Mexico City and the Gulf of Mexico, experiments have been conducted every year since 1949, with the exception of 1952, for the purpose of determining the practical value of this procedure for increasing streamflow through their hydroelectric plants on the Necaxa watershed. The seeding agent in this program was silver iodide. During the first five seasons, the silver iodide was dispensed from aircraft directly into the clouds moving across the watershed, but since 1953 the seeding has been from smoke generators on the ground, situated upwind from the target area. Because of the practical importance of realizing whatever increase in streamflow would be achieved, no random selection of unseeded situations was made prior to the 1956 season except from such accidental cause as equipment failure, especially failure of the aircraft to accomplish seeding missions for mechanical reasons during the first three years. However, since 1956 a proportion of seedable occasions, selected at random, was kept unseeded.

During the term of this experiment, a number of different analyses were made of the data, based principally upon rainfall comparisons between three different areas: one a lowland area entirely upwind of the target but having somewhat different climatic regime due to lower elevation; second, the lower half of the target area where presumably most of the rainfall may have been due to so-called warm cloud processes; and third, the upper half of the target area where mountainous elevations were such that considerable portions of the clouds must have been regularly above the freezing level. In many of the analyses, distinction was made between days with different rainfall amounts, in the expectation that the days of heaviest rainfall would be associated with cyclonic tropical disturbances which could not be presumed to be affected at all by the silver iodide seeding. The analysis that appears to be most significant from the statistical point of view was made by making a least squares regression comparison between the lower half and the upper half of the target area, the result of which indicated that the rainfall in the upper half, averaged throughout the term of the experiment, was approximately 9% heavier than that in the lower half, figure of significance indicated by the analysis being less than one chance in 10,000 that the increase was due to random causes. Other analyses indicated that the greater part of the increase occurred on days of moderate rainfall and that no increase was indicated for the days when seeding had not been done. As will be noted subsequently, the statistical indications must be considered in the light of a number of important reservations.

A brief series of trials was undertaken in the Lufira basin, at the Congo headwaters, in April 1951, near the end of the wet season. Bombs were dropped that, exploding within the clouds, dispersed dry ice. Out of five flights, two were unsuccessful in encountering supercooled clouds, while on three other flights "satisfactory" results were achieved, especially the last, which was followed by rain from a cloud that the experimenters believed would otherwise have produced only false cirrus.

In 1951, the Bolivian Meteorological Service experimented on a small watershed in a mountainous district by burning some 700 l of  $\frac{1}{2}\%$  solution of silver iodide in highway flare pots. No evaluation was attempted because of extreme variability of the local winds and the uncertainty as to where the smoke would become effective.

In Taiwan, experiments have been reported covering three dry seasons (roughly November through March). During the first season seeding was done from planes, but for the two subsequent seasons silver iodide generators on the

ground were used. Evaluation by a regression analysis of target and control rainfall indicated an over-all increase of 15% in target rainfall for the three seasons.

The silver-iodide seedings in British East Africa have already been referred to in the previous section. Silver iodide mixed with gunpowder charges carried by balloons and exploded in clouds were without discernible effect.

Begun in 1951 on a commercial basis, the cloud-seeding project in Peru has been operated for the past 5 yr by a local entity under the technical guidance of the commercial meteorologists. Silver-iodide seeding from the ground is carried out during suitable weather throughout the year except during the height of the dry season and during periods of flood. It affects portions of three coastal river valleys—the Moche, Chicama, and Jequetepeque—and some adjacent highland areas in a district encompassing about 3,500 sq miles. The divide limiting the watershed attains a mean elevation of about 12,500 ft, with a few peaks exceeding 14,000 ft. Rainfall increase was evaluated by a target-control regression for each calendar month from 10 yr of history, normalized by a cube-root transformation. Evaluations subsequent to the initial one indicated an average increase from 1953 through 1955 of 25%, significant at the 0.001 level. Streamflow was also evaluated based on a regression of the flows in the target rivers and a river adjacent on the north, normalized by logarithmic transformations, which indicated for the same period a 44% increase significant at the 0.01 level. Subsequently to 1955, changes in the rain-gauge network and diversion of water into the control river forced abandonment of the established evaluation formulas. A program of randomization is now (1959) being initiated.

The longest available series of operations in Cuba has been conducted over the plains region adjacent to the southern coast of Camaguey Province and extending some 30 miles inland. After the first two seasons of operation in 1951 and 1952, a rainfall evaluation was made by regression methods using as control 10 yr of record over neighboring sugar cane lands, the density of rain gauges in these areas being high. The same regressions, substantially unaltered, have been used to evaluate subsequent seasons of operation in 1953, for February and March of 1954, and for a large part of the time since May 1956. Omitting the 1954 operations, which included both water and silver iodide seeding, evaluations made subsequent to the one that established the regressions have shown increases varying from 9% (whole year, 1957) to 42% (8 months, winter of 1958-59) and averaging 21% for 32 months of operation. The combined water and silver iodide seeding in 1954 indicated an increase of 61%. The significance levels indicated for these results surpass the 0.001 level.

Two other projects in Cuba and one in Puerto Rico have similarly gone into second seasons of operation after an evaluation regression had been established. In 1955, a second-season operation at Central Baltony, in southern Oriente Province, indicated a 12% increase and another at Central Fajardo, in Puerto Rico, indicated a 27% increase. In 1957, a second-season operation at Central Manati, in northwestern Oriente, turned in a 15% increase.

A series of experiments were conducted in March and June of 1954, and January, 1955 in three widely separated areas in the Belgian Congo, using silver-iodide from smoke generators on the ground. In the first of these, at Temvo, target and control rainfalls were compared for 7 seeded and 22 unseeded days, indicating an increase for which significance at the 0.01 level was claimed. The second experiment, at Mayumbe, is reported to have produced positive results in 7 out of 9 seedings. The third, at Tely, was even more brief,

seeding taking place on 2 days out of 10, on both of which precipitation was observed downwind from the generators, but not upwind.

For about a month in the late summer of 1956, and again in August, 1957, silver-iodide seedings from the ground into cumulus clouds were effected near Boca Raton, on the southeast coast of Florida. The cloud behavior was recorded by time-lapse photography and by radar, and computations of precipitation initiation in 21 of these clouds were performed by MacCready's graphical method.<sup>(39)</sup> The observed onsets of rain and radar echoes agreed well in most cases with the trajectories computed for coalescence rain, though in a few cases rain and radar echoes appeared sooner than predicted by the computations, deviations which may be attributed to non-fulfillment of the assumed up-draft conditions since these non-conforming clouds formed over the ocean rather than, as did the others, over the land. Large sheets of ice-crystal cloud, forming after the showers, were taken as evidence that the sublimation process, although not the initiating process, contributed to the precipitation at a later stage in the cloud life and can be a contributing factor to total rainfall. It was concluded that there is no possibility of detecting precipitation initiation by silver-iodide because the sublimation process operates too slowly.

The seedings in Arizona in the summers of 1957 and 1958 produced a 30% increase in rainfall which, while not in itself of acceptable significance, was associated with increased frequency of lightning and more frequent appearance of radar echoes in warmer parts of the clouds that were considered statistically significant.

The rest of the available data sources are mostly commercial operations operated for one season only, or for the initial seasons of projects discussed above. These, together with the indicated results where evaluation by the regression method has been made, are summarized in Table 4. While judgment as to the impartiality of the results must be reserved until independently tested, it is noteworthy that the indicated increases fall in the same range as those for which impartiality may be claimed.

One other operation has been conducted that falls in a different category because the purpose of the seeding was not to increase rainfall but to diminish the damage caused by local winds accompanying heavy showers. These operations were conducted in northern Colombia, in the lee of the Sierra Nevada de Santa Marta,<sup>(44)</sup> which juts up as a more or less conical obstruction in the trade winds. The seeding was carried out during two storm seasons in 1956 and 1957, for a total of 12 months of operation. Analysis of the results was based on the damage reported in selected banana plantations. The data indicated that the ratio between the frequency of severe storms and light storms was decreased markedly, with significance at the 0.001 level, and suggested that this came about through a decrease in the frequency of severe storms rather than through an increase in the frequency of the light storms, although this conclusion could not be supported with confidence at the 5% level. If the latter conclusion is assumed true, then the wind damage was decreased about 39% by the seeding.

In attempting to draw any general conclusions about the effectiveness of silver-iodide or dry ice seeding in the tropics from these data, it should be remembered that most of the evaluations have been made by the target-control regression method and that this method is open to question on a number of grounds. Although the choice of rain gauges, to characterize the target, is generally automatic, and the choice of a historical period is usually largely so, the choice of a control region is more or less subjective, and its selection influences the outcome of the evaluation. It is furthermore assumed that the

target-control relationship that prevailed during the historical period would prevail also during the experimental period in the absence of seeding, an assumption that, though it seems reasonable and has not been proven invalid, is open to question because of secular changes in rainfall climate that are known to occur. Finally, details on the treatment of the data affect the evaluations to some extent. Because of these factors, it is generally thought that only trials following a rigidly randomized and pre-ordained plan, such as that followed in the Arizona project, can be used in drawing valid conclusions regarding the reality of the seeding effect. Nevertheless, the bulk of less certain evidence suggests that one should be slow in accepting a hypothesis that silver-iodide seeding is ineffective in the tropics, and it invites attention to the search for understanding of possible considerable effects.

### COALESCENCE RAINFALL

*Theoretical studies.*—A fairly well-developed model for the formation of precipitation by a coalescence process, that can take place in clouds of any

TABLE 4.—COMMERCIAL ONE-SEASON PROJECTS FOR  
CLOUD-SEEDING WITH SILVER-IODIDE

Date	Location	Duration, in months	Increase, in %	Probability
1951-56	Peru, Rio Mantaro	30	20	.07
1951-52	Cuba, Francisco	15	27	.08
1953	Cuba, Los Canos	3	20	---
1953	Cuba, Macareno	6	20	---
1952	Cuba, Cespedes	3	25	.04
1952	Cuba, Ermita	7	46	.005
1952	Cuba, Macareno	5	35	---
1952	Cuba, Najasa	6	33	---
1953	Cuba, Baltony	3	15	---
1953	Cuba, Preston & Boston	3	19	.002
1953-54	Puerto Rico, Fajardo	2	14	---
1956	Cuba, Havana-Matanzas	3	27	.03
1956	Cuba, Manati	3	15	.21
1957	Puerto Rico, south coast	2	42	.05
1957	Hispaniola, Romana	4	31	.10
1957	Cuba, Esperanza	2	27	.06
1957	Cuba, Los Canos	2	21	.02

<sup>a</sup> Seeding with salt spray was carried out simultaneously from the air.

temperature but is favored by the high liquid water contents typical of tropical clouds, has emerged from the suggestion by H. G. Houghton(45) that the few particles at the large end of the drop-size spectrum play an important part and the work of E. G. Bowen,(46) E. J. Mason,(47) F. H. Ludlam,(48,49,50) C. H. Keith and A. B. Arons,(51) T. W. R. East,(52) and many others in developing quantitative expressions for the growth of droplets by coalescence. These have been used by MacCready(39) to develop graphs which he used successfully in Project Shower to predict the time of onset of precipitation and to indicate whether the precipitation was initiated by coalescence or by the Bergeron-

Findeisen process. The time necessary for the development of precipitation by coalescence within a cloud and its appearance as rain at the cloud base, as shown on the MacCready graphs, indicates that for clouds having a temperature of  $18^{\circ}\text{C}$  to  $20^{\circ}\text{C}$  and updrafts of 1 to 2 m per sec, the time from entry of an air parcel into a cloud until precipitation formed in it emerges is 34 min to 48 min, all but 12 min to 10 min of this being the time required for the rudimentary precipitation particles to reach 50 m in radius, assuming that the particles remain in a steadily rising column of air. If, as is often observed, the formation of a column of rain is accompanied by a downdraft, this latter time might be considerably shortened. The computed trajectories of the droplets during their growth carry them to elevations of from 5,000 ft to 10,000 ft above the cloud base, depending on the strength of the updraft. This picture is well confirmed by the observations of Louis J. Battan(19) that the probability of precipitation in clouds over Puerto Rico, where updrafts are comparatively strong, was very low for clouds less than 7,000 ft thick, increasing gradually to about 50% for clouds 12,000 ft thick, while over the sea, where updrafts are weaker, rain was very unlikely in clouds less than 6,000 ft thick but virtually certain if the cloud was more than 11,500 ft thick.

The purpose of cloud-seeding with water spray or hygroscopic particles is to short-cut the natural coalescence process by providing the cloud with a supply of rudimentary precipitation particles already nearly or quite large enough to begin falling. If the seeding is successful, rain should emerge according to MacCready's charts anywhere from 10 min to 12 min after the particles reach the interior of the cloud, to which time must be added, if the seeding is done from the cloud base, the time during which droplets are being carried upward to the region of the high liquid-water content. If downdrafts are present or develop along with the formation of precipitation, the fall time will be considerably shortened. If an updraft of 500 ft per min gives way to a downdraft equally strong, the emergence of rain from the cloud-base within 3 min or 4 min may be explained. On the other hand, if the cloud contains insufficient liquid water to nourish the growth of the seeding particles to raindrop size, the seeding may be expected to produce only drizzle or light virga which fails to reach the ground, accompanied by dissipation of the cloud. The seeding will likewise fail if the particles are rapidly carried to the outside of the cloud and entrained with drying air, or if the seeded portion of the cloud is carried away from its main body by shearing winds. Hence it is to be expected that successful seeding will be confined to clouds exceeding some minimum thickness, not suffering a strong wind shear or penetrating extremely dry air, and will be favored if the cloud is imbedded in a moist layer. The experimental evidence suggests that this critical limit of thickness lies near 4,000 ft for most lowland situations in the tropics, and that clouds between 4,000 ft and 8,000 ft thick are particularly susceptible to production of rain by seeding that would not otherwise fall. Theory and observation are in substantial agreement regarding the initiation of rainfall by a coalescence process in warm clouds and regarding the influence of salt or water seeding upon it.

It has been widely concluded as a result of this agreement that the presence of ice-crystals or ice-forming nuclei plays no part in the initiation of precipitation from most convective clouds and only a secondary role in their subsequent development, and that there is, therefore, no basis for the supposition that silver-iodide or dry ice seeding should have any discernible stimulative effect on rainfall. Yet it is difficult to reconcile this conclusion with the results of observation.

## CONSIDERATIONS FOR A NEW MODEL

The writer's first survey of cloud conditions in Cuba, in 1951, showed the regular occurrence of convective clouds, over the land, that frequently reached the freezing level some hours before the onset of precipitation. The phenomenon of "cirrus pumping" was also observed, indicating that some clouds reached even the  $-40^{\circ}\text{C}$  isotherm where homogeneous nucleation caused them to glaciate without increase of particle size and flow off as separate cirrus umbrellas (Fig. 1). It appeared that the clouds frequently endured for some time in a supercooled state without raining or before the onset of rain, leading one to believe that silver-iodide seeding might be effecting in releasing rain.

These and other observations lead the writer to distinguish between two typical sequences of cloud development leading to showers. In Sequence I, nearly continuous and rapid growth carries the cloud from humble beginnings through the congested stage and on to cumulonimbus in perhaps  $\frac{1}{2}$  hr or 1 hr. This oc-

currs typically when instability is released by a definite impulse such as the arrival of a seabreeze front. As the cloud develops, rudimentary precipitation particles form much faster than they are lost, and rain begins promptly, as soon as the first formed particles are sufficiently aged. Rainfall is likely to be widespread in the general region where cloud development occurs.

Sequence II is marked by much more gradual growth of the clouds, even though they are convectively active. Typically, many clouds of nearly the same size may be seen that grow actively in their lower parts while dissipating above, the average size gradually increasing and the number decreasing. This state of affairs may continue until ended by the afternoon decrease in heating, or it may be terminated by the development of precipitation in one of the clouds. When precipitation does become well established in one cloud, it is hard to avoid the impression that the onset of precipitation is often connected with a marked increase in the rate of growth of the cloud and the degeneration of other clouds nearby, the rolling growth and dissipation in activity being replaced by swift organization of a large-scale convective cell. The ensuing rainfall, while sometimes heavy, is generally more spotty than that produced by Sequence I.

The impression of greatly accelerated growth and activity accompanying the onset of rain has also been reported, in many cases, where the rain followed efforts at stimulation and is apparent in many of the time-lapse movies that have been made of convective clouds and shower development. Indeed it seems to be a frequent accompaniment of shower development, whether stimulated or not.

Before the establishment of precipitation in a cloud, the alternate rising and subsiding of cloud turrets indicates that the buoyancy in the cloud, at the top of its trajectory, is negative; that is, the cloud is cooler and heavier than its surroundings, the cooling being due, at least in part, to evaporation of liquid water in unsaturated air that is entrained into the cloud. But when precipitation occurs, a mass of water that approximates, according to H. R. Byers and R. R. Braham, (53) some 20% of that in the circulation (and a higher percentage of the water in the active portion of the cloud) is removed. Not only is this much weight removed, but the heat that would otherwise have gone to re-evaporate a portion of this water as unsaturated air mixed with it remains in the upper part of the cloud and increases its buoyancy. The turrets from this cloud rise higher than those from competing clouds nearby and, entering



FIG. 1.—CIRRUS UMBRELLA

a slice of the atmosphere, where it is the only rising current present, find the atmosphere effectively more unstable. This convective circulation will then continue to increase in magnitude and depth, drawing on the whole of the moist layer as its source of moisture and energy, while its non-precipitating neighbors remain limited to drawing energy from its lower portion only. It may be that these several effects working together are responsible for the rapid cloud growth that appears to accompany the onset of showers. A sequence of photographs published by B. J. Mason,(54) illustrated this effect occurring under circumstances similar to those described. The last photograph of the sequence being reproduced here as Fig. 2.

If, indeed, the onset of precipitation tends to increase the convectivity of a cloud and hence its total production of rain, there should occur a discontinuity

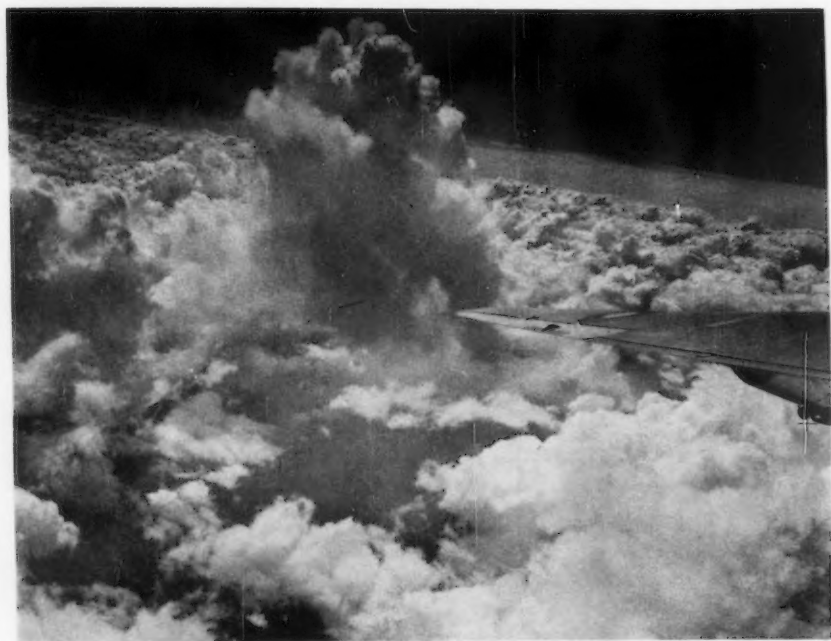


FIG. 2.—CONVECTIVE CIRCULATION

in the spectrum both of total rainfall and of duration of showers analogous to the discontinuity in the spectrum of cloud droplet sizes between activated and unactivated nuclei. The occurrence of a shower of very small size should be rarer than would be expected from the spectrum of large showers. Cursory examination of time-lapse movies of radarscopes does, indeed, suggest that the occurrence of very small showers of very short duration is less frequent than that of somewhat larger, more persistent showers.

Both cloud sequences, together with gradation between them, were observed during the Cuban seeding projects. Good correspondence between the areas of rainfall and the portions of smoke plumes at some 1 hr or 2 hr of wind travel

from the generators was immediately noticed in about a third of the maps, another third showing some weak connection, and the remainder none. Fig. 3 shows an exceptionally good connection. It was noticeable that most of the days when there were isolated, heavy showers showed good connection, while the connection was weak or absent when the rain was more general. The analyses, borne out by visual observations, suggested that the seeding was most effective under Sequence II conditions.

### THE FIELD OF COMPETITION MODEL

Consider not a single cloud but a horizontally extended portion of atmosphere overlying a source of warmth and moisture so that a moist unstable layer is overlain by drier air. This constitutes a field within which a number of convective cells compete for potential energy, slowly warming and deepening the surface layer as they increase gradually in size and decrease in number. This field of competition will contain a number of clouds that in their maturer stage are nearly equal in size and in which the probability of precipitation is nearly equal.

Following F. H. Ludlam(50) and others, the writers regard the cloud as a series of bubbles that entrain air from the environment, gaining energy in the lower part of the cloud but, at its top, cooling by evaporating and subsiding, leaving a more moist environment for the next bubble. Some fraction of the largest cloud droplets that form in the bubble may be regarded as rudimentary precipitation particles which, if they survive long enough in the cloud, will become rain drops. The rate at which rudimentary precipitation particles form depends upon the concentration of large hygroscopic nuclei, occurrence of collisions, etc., while their survival in the evaporating part of the cloud, or if they are thrown out of it, depends on their being large enough to maintain their existence until they are re-entrained or fall back into the cloud. Ludlam(50) has estimated that droplets smaller than  $150 \mu$  will be lost, and those larger will fall back into the cloud and continue growing. One may think of the progress of the cloud toward the shower stage as measured by the net accumulated age, or let us say the accumulated seniority, of the rudimentary precipitation particles working in its rain factory. If but few particles become rain drops, they will fall singly, not as a shower, thus it seems that some minimum accumulated seniority must be achieved before a shower can fall. New condensation adds to the working force, and high liquid-water content in the cloud promotes rapid aging; conversely, entrainment of drier air delays aging, and evaporation of the upper part depletes the ranks of the senior workers. In fair-weather cumulus, especially over land, even though some fair-weather cumulus may contain enough liquid water for a shower, the accumulated seniority never becomes great enough to produce it. However, if precipitation does become established, the processes discussed under the heading "Consideration for a New Model" will lead to acceleration of the growth of that cloud.

As the clouds within the field of competition grow, their collective approach to the rain stage may be described as a frequency distribution of what has been termed "quantity of seniority" in each cloud's rain factory. By the time the percentage of clouds with seniorities surpassing the critical limit for rain formation reaches a few percentages, it becomes very likely that rain will begin somewhere in the field, followed by rapid growth of the successful cloud and the subsidence of convective activity elsewhere.

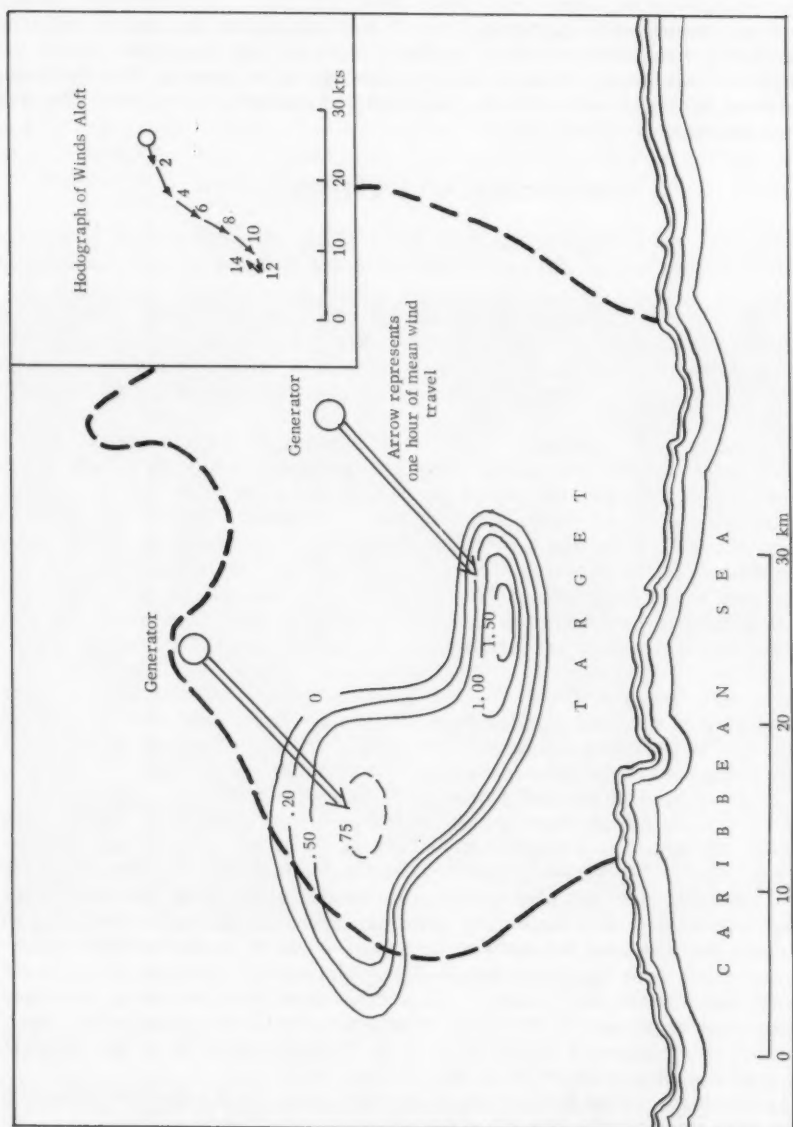


FIG. 3.—RAINFALL AND SMOKE AREAS

If one of the competing clouds is seeded with water droplets or hygroscopic particles, during the approach to the critical stage, in effect giving it a large number of ready-made rudimentary precipitation particles, the seeded cloud is boosted somewhat higher on the seniority scale than its neighbors, perhaps by merely a few percentages. Even these few percentages, however, place the seeded cloud at a large advantage and greatly increase the probability of its becoming the first successful rain producer.

If the seeding agent is silver-iodide, no effect is to be expected until the cloud tops reach a temperature of about  $-5^{\circ}\text{C}$ . But when this temperature is reached, some ice-crystals will appear in the seeded cloud and some of the rudimentary precipitation particles will freeze either through collision with an ice-crystal or through infection with silver-iodide. These particles will be able to grow anywhere in the region where air is saturated with respect to ice, even where water droplets are evaporating, and even in dry air the freezing particles evaporate more slowly. Furthermore, as R. H. Douglas(55) has shown, the freezing particles may grow as much as twice as fast by accretion as their unfrozen neighbors. Hence the rate at which the seeded clouds lose rudimentary precipitation particles is diminished by virtue of their becoming frozen, and the rate at which they acquire seniority is increased. As noted previously, the seeded cloud is given an advantage that expresses itself in the form of a much-improved chance that it will be the one in the group that will first develop precipitation. This effect of silver-iodide seeding operates through the coalescence mechanism, so it is unnecessary to postulate the independent growth of any rudimentary particles in the form of ice-crystals entirely by sublimation in order to account for an effect of silver-iodide seeding that will in many regards resemble the effect of a warm-cloud seeding.

When precipitation is released by seeding, the ensuing chain of events feeds energy to the seeded cloud from a much larger portion of the atmosphere than it could otherwise have reached. In effect, the "signal" energy released directly by the seeding is amplified many times, and the output is determined not so much by the strength of the signal as by the energy resources of the system.

## CONCLUSIONS

In 1954, the World Meteorological Organization's study of induced rainfall in arid regions, principally in the tropics, concluded that operations up to that time were, at best, inconclusive, and although the contributors eschewed any estimates of quantitative increases, the impression given by the report is that then-current techniques of seeding should not be expected to give easily demonstrable increases. It concluded further that these techniques would have very little if any value in augmenting rainfall during very dry periods or in very dry areas, and that the most favorable conditions are to be sought in regions where, and during seasons when, natural precipitation is most likely.

Now, after approximately five more years of experience, it is possible to state that the results of experimentation, while open to questions of interpretation regarding conclusiveness, suggest very strongly that present techniques of cloud-seeding in the tropics, can increase the rainfall locally by very considerable percentages, not only at naturally rainy locations and times, but also at many places and times where rainfall deficit is now a major source of economic loss. It appears that of the two principal techniques, "warm" cloud-seeding with hygroscopic particles or water spray and "cold" cloud-seeding

with dry ice or silver-iodide, the former is of more general applicability and greater effectiveness, but that the latter is far from being ineffective in many situations in the tropics. The suggestion is further made that artificial influences may be most effective when clouds approach the rain stage more or less gradually, as they frequently do in extensive plains areas, and that under these circumstances silver-iodide seeding, simultaneously with spray or hygroscopic-particle seeding, will increase the effectiveness of the latter.

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GENERATOR TECHNOLOGY FOR CLOUD SEEDING<sup>a</sup>

By D. M. Fuquay<sup>1</sup>

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SYNOPSIS

This paper describes experiences in the development and calibration of solution and string-type silver-iodide generators for use on Project Skyfire lightning studies.

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INTRODUCTION

Many devices have been developed to produce ice-forming nuclei since B. Vonnegut first discovered that silver iodide particles serve as nuclei for the formation of ice crystals.<sup>2</sup> These devices have been of many forms from a simple candle burning a wick impregnated with silver iodide through various pyrotechnic devices and electric arc units to fairly large forced-draft furnaces burning coke that had been saturated with silver iodide.<sup>3</sup> In general, generators in common use can be grouped into three main types depending on the technique of delivering silver iodide to a burner. These types are coke, string, and solution-burning generators. The output and the efficiency of many

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

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<sup>2</sup> "The Nucleation of Ice Formation by Silver Iodide," by B. Vonnegut, J. Applied Phys., 18, 593-595.

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of these devices has been reported in the literature, but some of the data are conflicting.

The primary objective of most silver iodide smoke generator engineering has been the development of a mechanical device that will operate satisfactorily without considering the type and nature of the crystals that should be produced. However, only a few data have been available on the desirable characteristics of nuclei for cloud seeding or on the features of a generator designed for optimum nuclei production.

Recent additions to the literature have included theoretical studies of the size of nuclei most suitable for cloud seeding and the behavior of silver iodide. N. H. Fletcher has derived, from fundamental thermodynamics, a theoretical relationship between the surface properties of crystals, the size of a spherical nucleus and the subcooled temperature at which these nuclei will be active in heterogeneous nucleation.<sup>4</sup> In a subsequent paper, Fletcher shows<sup>5</sup> how the application of classical nucleation theory can help explain many aspects of the behavior of aerosol particles as ice crystal nuclei. A size effect was calculated which could explain the observed distribution of activity in smokes. Fletcher applies theoretical aspects of nucleation to derive a theoretical maximum activity curve for silver iodide smokes.<sup>6</sup> The output of real generators, when compared with the theoretical maximum values, indicates that some generators are operating near optimum efficiency.

A program to improve nuclei production techniques and nucleation efficiency should include the evaluation of past generator development as well as consideration of the theoretical aspects of nuclei production. This paper summarizes the writer's experience in the development and calibration of solution and string-type generators for use on Project Skyfire lightning studies.

### COMPARATIVE STUDY OF SILVER IODIDE SMOKE GENERATORS

During the winter of 1956-57, a generator calibration and development program was carried out to accomplish the following objectives:

1. To make a comparative calibration of all available generators used or considered for use in the lightning-suppression experiments;
2. To investigate the effects of design changes on the output and efficiency of generators; and
3. To determine nuclei-production rates that are necessary to evaluate cloud-seeding operations.

A comparative calibration was made of the output of effective silver iodide nuclei from three string-type generators and two generators of the solution-burning type. These generators were compared for: (1) rate of production of effective silver iodide crystals; (2) number of nuclei produced per gram of silver iodide used; (3) consumption rate of other materials such as acetone and propane. Unfortunately, no coke-burning generators were available at the time

<sup>4</sup> "Size Effect in Heterogeneous Nucleation," by N. H. Fletcher, *J. Chem. Phys.*, 29, 572-576.

<sup>5</sup> "On Ice-Crystal Production by Aerosol Particles," by N. H. Fletcher, *J. Meteor.*, 16, 173-180.

<sup>6</sup> "Optimum Performance of Silver Iodide Smoke Generators," by N. H. Fletcher, *J. Meteor.*, Aug. 1959.

these studies were made. However, G. Soulage had previously reported on the output from several coke-burning generators.<sup>7</sup>

**Calibration Technique.**—The following technique, similar to that used<sup>8</sup> by Vonnegut was used to determine generator output. The smoke from a generator being calibrated was mixed with a large volume of air flowing at a known rate through a vertical wind tunnel. A metered sample was taken from the mixed air stream, diluted by a known amount of clean air, and introduced into a cold box. Each silver iodide crystal effective at the cold-box temperature was assumed to cause an ice crystal to grow to visible size in the subcooled fog already present in the cold box. Visual counts, with the aid of a low-power microscope, were made of all crystals formed in a known volume in the cold box. Counts were made up to 3 min after the sample was introduced into the cold chamber. Nuclei counts were made at cold-box temperatures from  $-22^{\circ}\text{C}$  to  $-6^{\circ}\text{C}$ .

**String-Type Generators.**—The activity curves of the output from three string-type generators are shown in Fig. 1. Curve 1 was taken from a standard string type that consumed 0.9 of silver iodide per hr according to the manufacturer. The string, prepared by saturating a hank of cord in a 10% silver iodide-sodium iodide-acetone solution, was fed into the shaped flame of a standard propane air torch at a rate of 2.5 cm per min. Curve 2 was for a high-output, string-type generator. The principle of operation was the same as for the standard type except that the string feed was 10 cm per min (14.5 g of silver iodide per hr using string prepared in the laboratory for this study) and an oxy-propane flame was used to burn the string.

The output from a modified string-type generator is shown by curve 3. The only modification was that the string was burned in an open propane flame contained in a ceramic flame chamber instead of in a shaped-flame. The consumption rate was about 14 g per hr. The crystal production efficiency is shown by correspondingly numbered curves in Fig. 2.

The curves in Fig. 1 and 2 represent an average maximum output from these generators. The nuclei-production rate varies considerably in the string-type generator. This is probably due to an uneven distribution of silver iodide on the string. One interesting feature of these curves is the apparent change in the slope of the production curve at about  $-12^{\circ}\text{C}$ . The rate of change of output per degree change in cold box temperature is much greater at temperatures warmer than  $-12^{\circ}\text{C}$ . Fletcher mentions<sup>6</sup> that the sharp-angled curves indicate the production of a very homogeneous smoke. The fact that the maximum production rate occurs at relatively cold temperatures ( $-15^{\circ}\text{C}$ ) suggests the production of crystals smaller than about 700. The string generator does not appear to be suitable for any use requiring the production of a large number of crystals effective at relatively warm temperatures. However, economical operation and low support requirements would recommend this type of generator where these defects would not be particularly detrimental.

**Solution-Type Generators.**—The output rate and efficiency curves for two solution-type generators appear in Fig. 3 and 4. Curve 1 in Fig. 3 is for a generator using a "Spraco" internal mixing paint spray nozzle. In this generator, similar to those used on many commercial and research cloud-seeding

<sup>7</sup> "Etude de Generateurs de Fumees d'Iodure d'Argent," by G. Soulage, Bull. Obs. Puy de Dome., 3, p. 1.

<sup>8</sup> "Early Work on Silver Iodide Smokes for Cloud Seeding," by B. Vonnegut, Final Report, Advisory Committee on Weather Control, U.S. Congress, 1957, Vol II, 283-285.

projects, a solution of silver iodide, sodium iodide, and acetone is forced by propane pressure through a spray nozzle into a steel combustion chamber where the solution is burned. The solution flow rate is controlled by a needle valve in the spray nozzle. The consumption rate was 33 g of silver iodide and 7 to 8 lb of propane per hr. Curve 2 in Fig. 3 is from another generator using a paint-spray nozzle, but this generator was designed for airborne use (by the California State Division of Forestry). In this generator, a silver iodide solu-

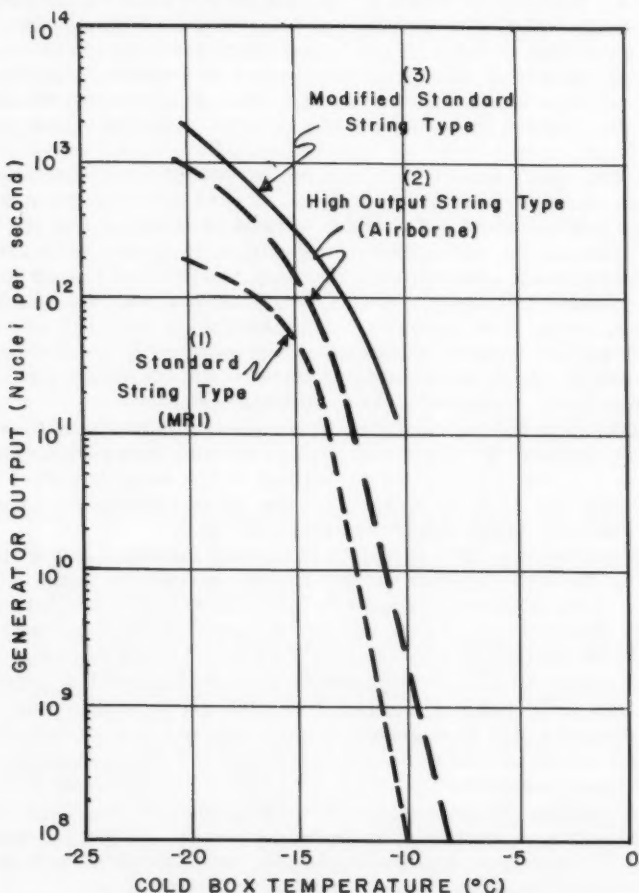


FIG. 1.—THE PRODUCTION RATE OF EFFECTIVE SILVER IODIDE NUCLEI FOR THREE STRING-TYPE GENERATORS.

tion is forced through a paint-spray nozzle by air pressure. Acetylene gas, at 7 lb pressure, is mixed with the solution in the nozzle and the atomized mixture is directed into a flame chamber and burned. The generator consumes about 30 g of silver iodide per hr in normal operation.

*Accuracy of Calibration Procedure.*—Many questions can be raised on both the probable accuracy and the interpretation of these data. The question of the

applicability of a cold box to simulate what might happen in a natural cloud has been discussed by others and is not argued further here. For this study, the errors due to characteristics of the cold box were kept to a minimum by holding the concentration of crystals in the cold box nearly constant ( $10^3$  to  $10^4$  per l) and measuring the concentration by changing the dilution of the effluent. Systematic errors could still be present since the characteristics of the cold box over the temperature range  $-6^\circ\text{C}$  to  $-22^\circ\text{C}$  are not known. A comparison of

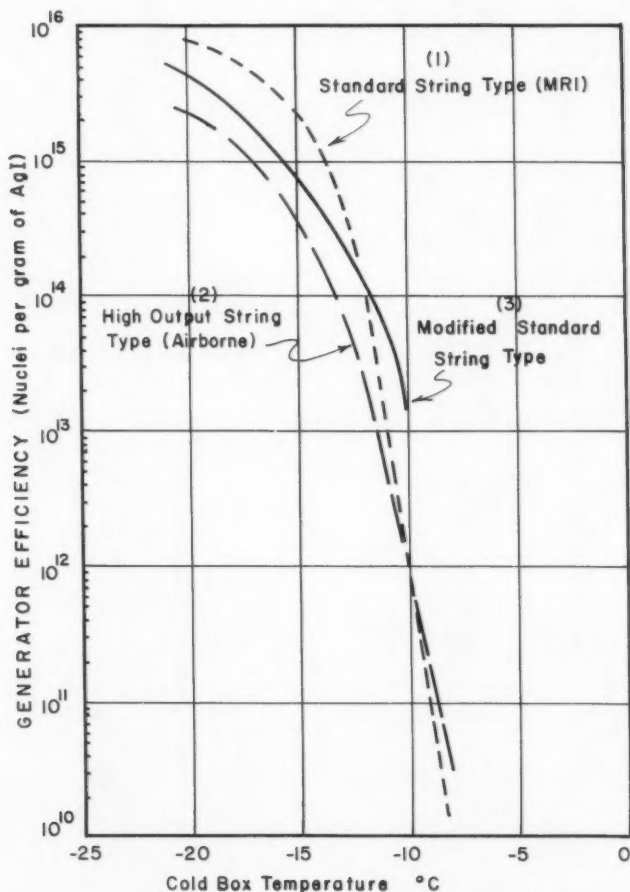


FIG. 2.—THE PRODUCTION EFFICIENCY OF THREE STRING-TYPE GENERATORS.

the type cold box used in these experiments with a larger cold chamber showed the absolute values reported here to be high by a factor of 5. However, since identical equipment and procedures were used on all calibration tests reported here, comparative outputs of the various generators should be realistic. Even after considering all reasonable sources of error, the comparative outputs should be accurate within a factor of 2 or 3.

*Supplementary Studies.*—After the comparative calibration of available generators was completed, many questions remained unanswered. These include such questions as the effect of flame temperature, quench rate, shape of flame chamber, and solution injection rate on the number of effective nuclei produced by a generator.

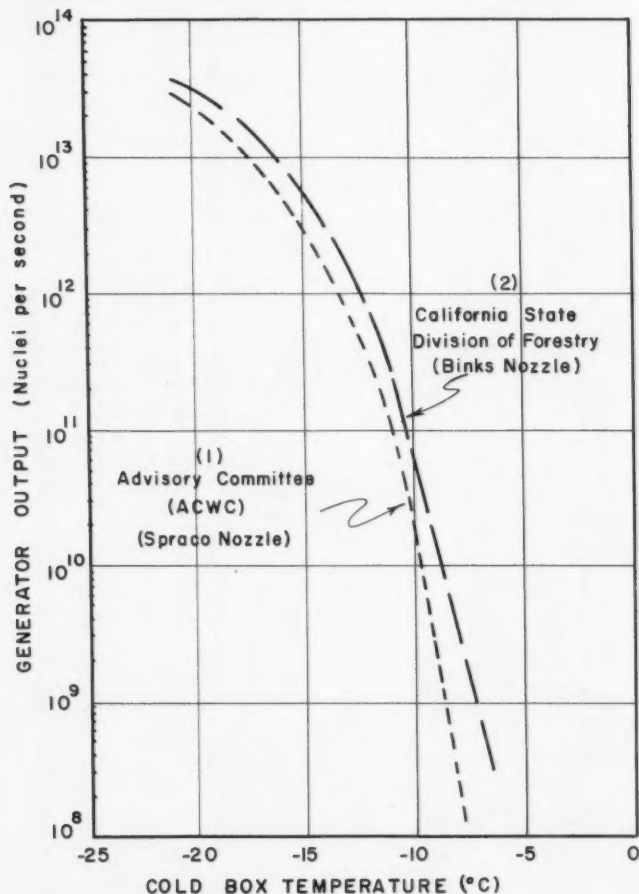


FIG. 3.—THE PRODUCTION RATE OF EFFECTIVE AgI NUCLEI FOR TWO SOLUTION-TYPE GENERATORS.

A series of rudimentary tests was performed to gather the necessary data. These tests showed that the characteristics of the flame chamber considerably affected the efficiency and output of a generator. Also, the proper mixture of solution, air, and gas was necessary to maximize the production of nuclei. The temperature in the flame chamber was varied by changing the amount of gas and air mixed with the solution. The output of nuclei increased linearly as the

temperature was increased from about 450°C to 1200°C; the rate of increased output decreased at temperatures above 1200°C. About 1200°C appeared to be the most efficient operating temperature for all flame chambers tested.

The necessity of maintaining 1200°C temperature within the flame chamber placed severe limitations on the design of the burner. The effect of quenching time on nuclei production was investigated by reducing the quench path from an insulated cylinder 2 m in length to a plate directly over the flame chamber.

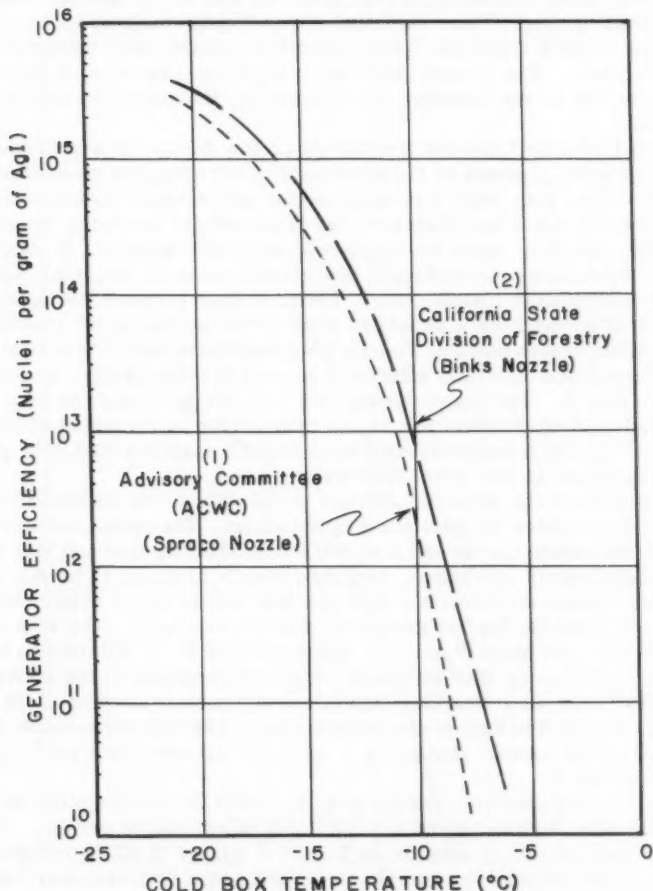


FIG. 4.—THE PRODUCTION EFFICIENCY OF TWO SOLUTION-TYPE GENERATORS.

Production rate increased five-fold by reducing the quenching length as much as possible.

Attempts were made to increase the generator output by injecting chemicals in addition to the silver iodide into the flame. In some tests, the output was increased threefold by injecting iodine vapor into the burner. However, the use of heated iodine crystals was considered dangerous to personnel. Ammonia vapor kept the burner free of deposits, but did not change the generator output.

## THE SKYFIRE GENERATOR

The Skyfire ground-based generator was designed to utilize the information gained from the calibration program. The development and testing of the generator has been described fully.<sup>9</sup> In this generator, silver iodide dissolved in a solution of acetone and sodium iodide is drawn from a reservoir through a modified hypodermic needle and nebulized by a jet of propane gas. This mixture of atomized acetone solution, propane, and air is directed into a flame chamber and ignited. The volatilized silver iodide condenses into crystals as the smoke passes from the flame around a quench plate mounted above the flame chamber. The quench plate serves the dual function of containing the mixture in the flame chamber and dispersing the smoke immediately above the flame.

In addition to the technical limitations on the design of a generator, other limitations were imposed by the conditions under which the generator would be operated. This generator was designed for operation in mountainous country and in forested areas and therefore had to satisfy the following requirements: First, the generator must be absolutely safe; particularly, it should create neither a fire hazard nor endanger operating personnel. Second, it must operate up to 8 hr without maintenance. Third, it must produce the highest possible output of nuclei from a minimum of materials to reduce the logistics problems in mountainous terrain. Fourth, the generator must be simple to operate.

The production rate and efficiency curves for the Skyfire generator are shown in Fig. 5. The consumption rate for this generator is 16 g of silver iodide and 1 lb of propane per hr. A comparison of the output of the Skyfire generator with the theoretical maximum output<sup>6</sup> suggests that this generator may be operating at near ideal efficiency.

An estimate of the mass distribution in the effluent would indicate the efficiency of a generator for particular applications. The mass distribution in a silver iodide smoke can be calculated if the production rate and size distribution of the crystals are known, and the crystals assumed to have a spherical shape. The measured production rate of silver iodide nuclei active in the range  $-6^{\circ}\text{C}$  to  $-24^{\circ}\text{C}$  for the Skyfire generator appears in Fig. 5. The size range for this generator was found<sup>10</sup> by H. E. Kissinger and E. Z. Mitchell to be  $10^{-2} \mu$  to  $10^{-1} \mu$ . Assuming that this size range corresponds to the activity range  $-6^{\circ}\text{C}$  to  $-24^{\circ}\text{C}$  and the activating temperature is a linear function of the particle diameter, a size distribution can be estimated. The calculated mass distribution based on the median diameters in nine size classes from  $10^{-2} \mu$  to  $10^{-1} \mu$  is shown in Fig. 6.

The calculated generator output (Fig. 6) based on the measured nuclei output and the size distribution is  $6 \times 10^{-3}$  g of silver iodide per sec. The consumption rate of this generator is  $5 \times 10^{-3}$  grams of silver iodide per sec. This agreement between consumption rate and output indicates that this generator is very efficient in producing active nuclei. However, the amount of nuclei utilized in a particular process depends on the temperatures involved in the process. For example, about one-half of the silver iodide in the output of the Skyfire generator is effective at temperatures warmer than  $-15^{\circ}\text{C}$ . If this generator were used in an application requiring nucleation at temperatures

<sup>9</sup> "The Project Skyfire Cloud-Seeding Generator," by D. M. Fuquay and H. J. Wells, Research Paper 48, Intermountain Forest and Range Expt. Sta.

<sup>10</sup> "Crystallography of Silver Iodide Nuclei," by H. E. Kissinger, Report No. 5474, National Bureau of Standards.

warmer than  $-10^{\circ}\text{C}$ , it would be only 6% efficient if the amount of silver iodide in the smoke actually utilized in the process were the criterion for efficiency.

#### AN EXPERIMENTAL AIRBORNE GENERATOR

Several silver iodide smoke generators have been developed for airborne use. Most of these have been of the solution-type based on a design reported

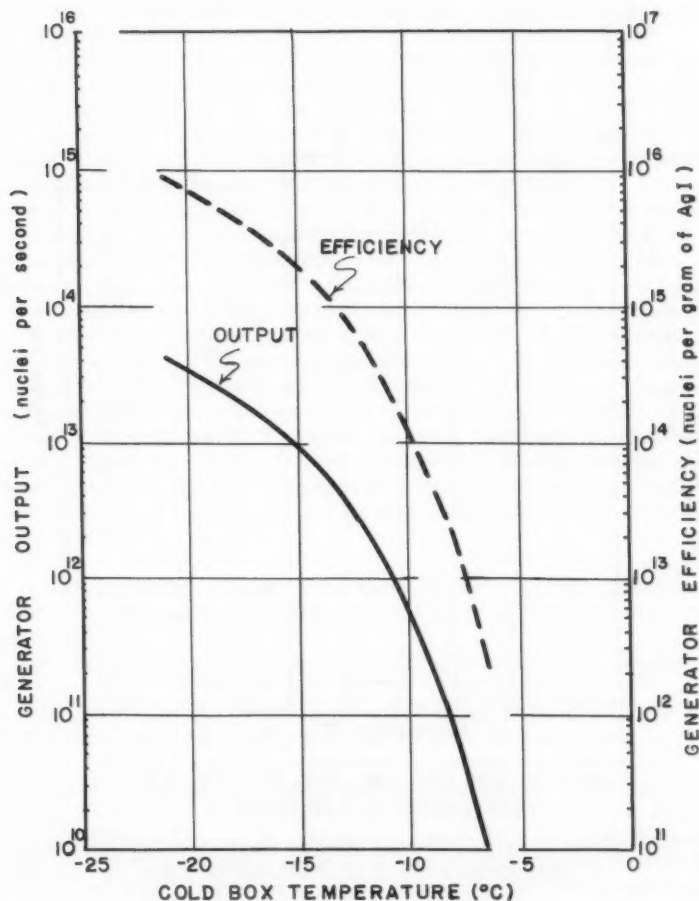


FIG. 5.—THE PRODUCTION RATE AND EFFICIENCY OF THE SKYFIRE GENERATOR.

by E. E. Adderley and S. Twomey.<sup>11</sup> The unit was originally designed for use on two-engined military aircraft. The basic design has been adapted for use

<sup>11</sup> "An Experiment in Artificial Stimulation of Precipitation in the Snowy Mountains Region of Australia," by E. E. Adderley and S. Twomey. Final Report, Advisory Committee on Weather Control. U. S. Congress 1957, Vol II, 291-295.

on light aircraft without apparent difficulty.<sup>12</sup> In general, this generator consists of a ram-jet unit affixed to the wing of the airplane outboard of the wing struts. Silver iodide solution is fed to the burner from a pressurized tank located inside the pilot's compartment. During the summer of 1956, an airborne string-type generator was used in experimental lightning-suppression studies.<sup>13</sup> The use of this type generator was discontinued because of its relatively low nuclei production rate (Fig. 3).

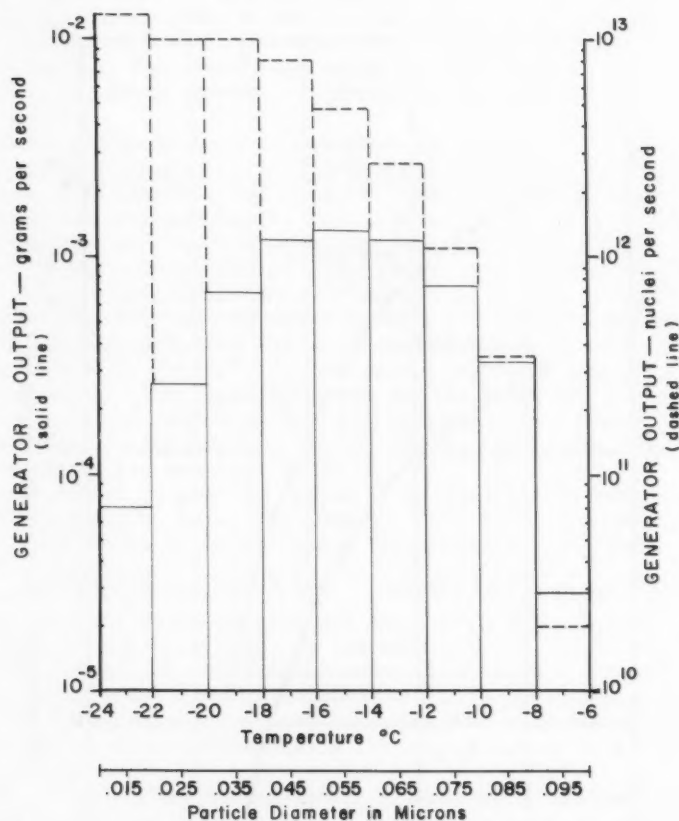


FIG. 6.—THE NUMBER OF EFFECTIVE NUCLEI AND THE MASS DISTRIBUTION IN THE SMOKE FROM A SKYFIRE GENERATOR.

*General Design Considerations.*—The problem of safety in handling acetone solutions and the design of equipment using acetone solutions probably has not been emphasized as much as it should be for cloud-seeding operations. Acetone is a dangerously flammable liquid and precautions should be taken to protect personnel and equipment, particularly in aircraft operation.

<sup>12</sup> "Randomized Seeding of Orographic Cumulus," by L. J. Battan and A. R. Kassander, 1957. Part I, Tech. Note 12, Cloud Phys. Lab. U. of Chicago.

<sup>13</sup> "Project Skyfire, Final Report, Advisory Committee on Weather Control," by J. S. Barrows, et al. U. S. Congress 1957, Vol II, 100-125.

Acetone, like ethyl ether and gasoline, is a Class I flammable liquid (National Board of Fire Underwriters) having a flash point below 20°F (closed cup test). Acetone is rated near ether, which has the highest hazard rating of 100 on the Underwriters' laboratory classification of flammable liquids.

While acetone rates quite low as a health hazard, the allowable dosage of 500 ppm to 2000 ppm could be exceeded easily and quickly if acetone should be released under pressure in a confined space such as the cabin of an aircraft. Overexposure to acetone leads to irritation of the mucous membranes, particularly in eyes, nose and throat, and to headaches, stupor, and a general feeling of oppression.

Possibility of explosion is perhaps the greatest danger from the accidental release of acetone under pressure into a confined space. The extremely low flash point (0°F) together with the very broad explosive limits of 2.6% to 12.8% in air makes acetone more dangerous than gasoline. Minor sparks from electrical equipment could easily ignite an acetone mixture in this explosive range. The auto-ignition temperature of this mixture is only 1,000°F.

Most cloud-seeding projects that rely on one or more single-engined aircraft for seeding must acquire these aircraft on a contract basis. When a piece of equipment, such as a silver iodide burner, is rigidly attached to the aircraft, the plane is then usually in the restricted-use category by Federal Aviation Agency regulations and is usually reserved exclusively for seeding operations. This exclusive-use feature can be expensive when one is contracting for an aircraft, particularly if the seeding operations use only a small part of the total available time of the aircraft. A generator that could be simply attached to the plane during seeding operations would release the aircraft from restrictions during nonseeding periods and possibly result in a substantial reduction in contract cost. This would be particularly true where several aircraft were contracted for seeding solely during periods of lightning and possibly hail activity.

A generator was designed for use on single-engined aircraft that would meet the following specifications:

1. A self-contained unit that could readily be mounted on a contract aircraft;
2. Have a nonpressurized solution source entirely independent of the pilot's compartment;
3. Have a simple, fail-safe control system that could be adapted to any aircraft;
4. Operate at high efficiency in the speed range of 80 mph to 140 mph; and
5. Not interfere with the flight characteristics of the aircraft.

*Design Features.*—Designs for a satisfactory solution-injection system and a burning chamber were developed concurrently because of the strong interdependence of these two parts. Since the solution system had to be nonpressurized, early attempts were made to design a venturi injector that would deliver 3 gal of solution per hr to a burning chamber. When the venturi was located in the intake channel, large deposits of silver iodide-sodium iodide accumulated on the walls of the channel because of the frictional transfer of momentum. As the size of the channel was increased, the volume of air became too large to maintain a stable flame in any reasonably sized burning chamber. Throttling the intake air resulted in inefficient burning of the solution and a subsequent low output from the generator. Attempts to move the injection system into the high temperatures of the burning chamber resulted in serious clogging of nozzles.

Two features appeared necessary for the proper operation of an airborne generator of this suggested design. First, the large flow of solution must be injected directly into an open flame chamber. Secondly, the large volume of air necessary to properly burn 3 gal of solution per hr and obtain a temperature of near  $1200^{\circ}\text{C}$  must be contained in a small volume. The following injecting and burning system was devised to fit these needs.

This generator consists of three main parts: a solution reservoir of about 10-gal capacity, an intake swirl chamber, and a burning chamber (Fig. 7). Air is rammed into the generator at A by the motion of the airplane through the air. This air is deflected into a high-velocity rotating air stream by the deflecting vanes B. The rotating air passes through opening C into flame chamber D. The centrifugal effect of the air rotating at point C results in a pressure reduction of about 30 mm of mercury at nozzle E. This pressure reduction is sufficient to start the flow of solution to nozzle E, where it is nebulized by the air stream and carried into the burning chamber D.

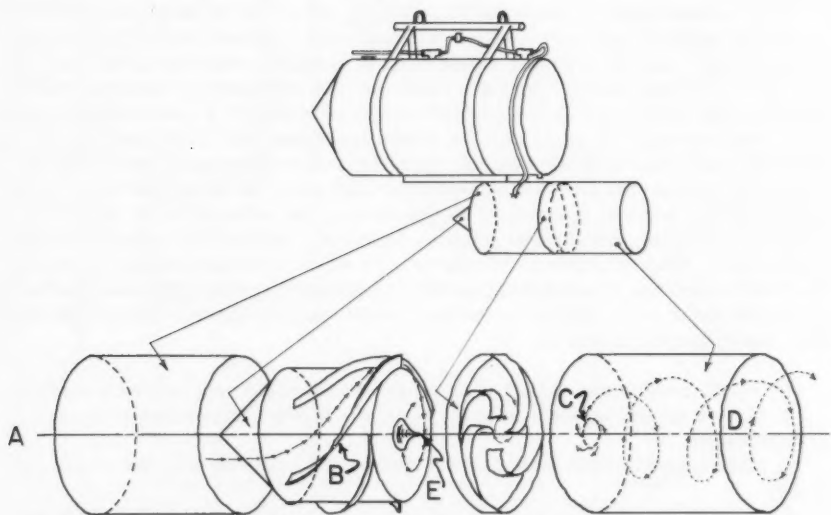


FIG. 7.—A SCHEMATIC DIAGRAM OF AN EXPERIMENTAL AIRBORNE SILVER IODIDE SMOKE GENERATOR.

The pressure reduction at C serves a further purpose than starting the flow of solution. The rapid rotation of the air causes a pressure reduction along the cylindrical axis of the burning chamber. This results in a counter flow of air along the outer wall of the chamber, which results in further containment of the air and insures uniform mixing in the chamber. This counter-current prevents solution from impinging directly on the walls of the chamber.

A high-voltage electrode, energized from a spark coil physically located inside the intake cone, ignites the mixture in the burner.

Valving of the silver iodide - sodium iodide - acetone solution has always been a problem in generators because of the clogging and corrosive effects of

the solution. A rather unique control system was devised so that the flow of solution could be started or stopped by a control signal through a single wire without the solution flowing through any control valves, Fig. 8. When the generator is in motion on an airplane, ram pressure at F forces air through the solenoid valve H and through the nozzle to the burner. The pressure is equal at G and I and no solution is moved from the reservoir. When solenoid valve H is energized, ram pressure is present on the top of the solution. The pressure reduction at the nozzle starts the flow of solution through tube J to the burner. The solution does not actually flow through the control valve. When the solenoid valve is de-energized, the flow of solution is stopped, and ram pressure purges the lines of any remaining solution.

This generator can be carried on a standard bomb rack under either wing of the plane. The bomb rack, which can be mounted on the wing at nominal cost, has been approved for Cessna 180 aircraft by the Federal Aviation Agency.

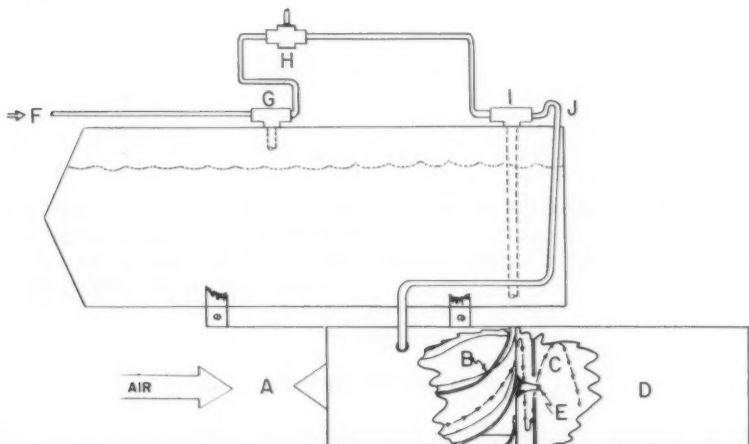


FIG. 8.—THE CONTROL SYSTEM FOR EXPERIMENTAL AIRBORNE SILVER IODIDE SMOKE GENERATOR.

The wires for controlling solution flow and ignition are connected through pull-out plugs at the mounting rack to a small control panel in the plane. In the event of an emergency landing, the pilot can jettison the generator by tripping the bomb-release switch. When control voltage to the generator is de-energized, the flame is completely extinguished in less than 5 sec.

This generator has been tested (as of 1959) several hours on the ground and about 20 hr in flight. After several minor modifications, the burner performed as planned. The generator burns with a stable flame of slightly higher than  $1000^{\circ}\text{C}$  for airplane speeds from 80 mph to 140 mph with no noticeable change in flame characteristics as the aircraft speed changes. A simulated flight calibration of output indicates the generator produces about  $10^{15}$  nuclei per sec effective at  $-20^{\circ}\text{C}$ . This indicates a production efficiency of about  $4 \times 10^{15}$  nuclei per g.

1. The first part of the paper discusses the importance of the study of the history of the English language. It is argued that the study of the history of the English language is essential for a full understanding of the language and its development. The paper then goes on to discuss the various factors which have influenced the development of the English language, such as the influence of other languages, the influence of social and cultural changes, and the influence of technological advances.

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CLOUD-SEEDING RESULTS IN SANTA CLARA COUNTY<sup>a</sup>

By Arnett S. Dennis<sup>1</sup>

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SYNOPSIS

An account is given of a cloud-seeding experiment conducted in Santa Clara County, Calif. during three consecutive winters starting with 1955-56. Analysis of results shows a probable increase in rainfall due to cloud seeding of from 15% to 28% of expected rainfall.

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INTRODUCTION

The first cloud-seeding experiments designed to increase rainfall in Santa Clara County were begun in December of 1951. The operations were ended early in January of 1952, as rainfall was above normal in much of California. A statistical analysis did not show any increase due to seeding.

Operations were resumed in the fall of 1954 and have been continued each winter since then. The period of operations for each season has been from December 1 to March 15 inclusive although some changes have been made to meet situations arising from excessive rainfall. The target area includes most of the agricultural land in Santa Clara County and the hills along either side of the Santa Clara Valley. Much of the rain falling on the hillsides is collected in reservoirs operated by the San Jose Water Works or the Santa Clara Valley Water Conservation District. The target area is shown in Fig. 1.

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August 1959 Weather Modification Conference in Denver, Colo.

<sup>1</sup> Weather Modification Co., San Jose, Calif.

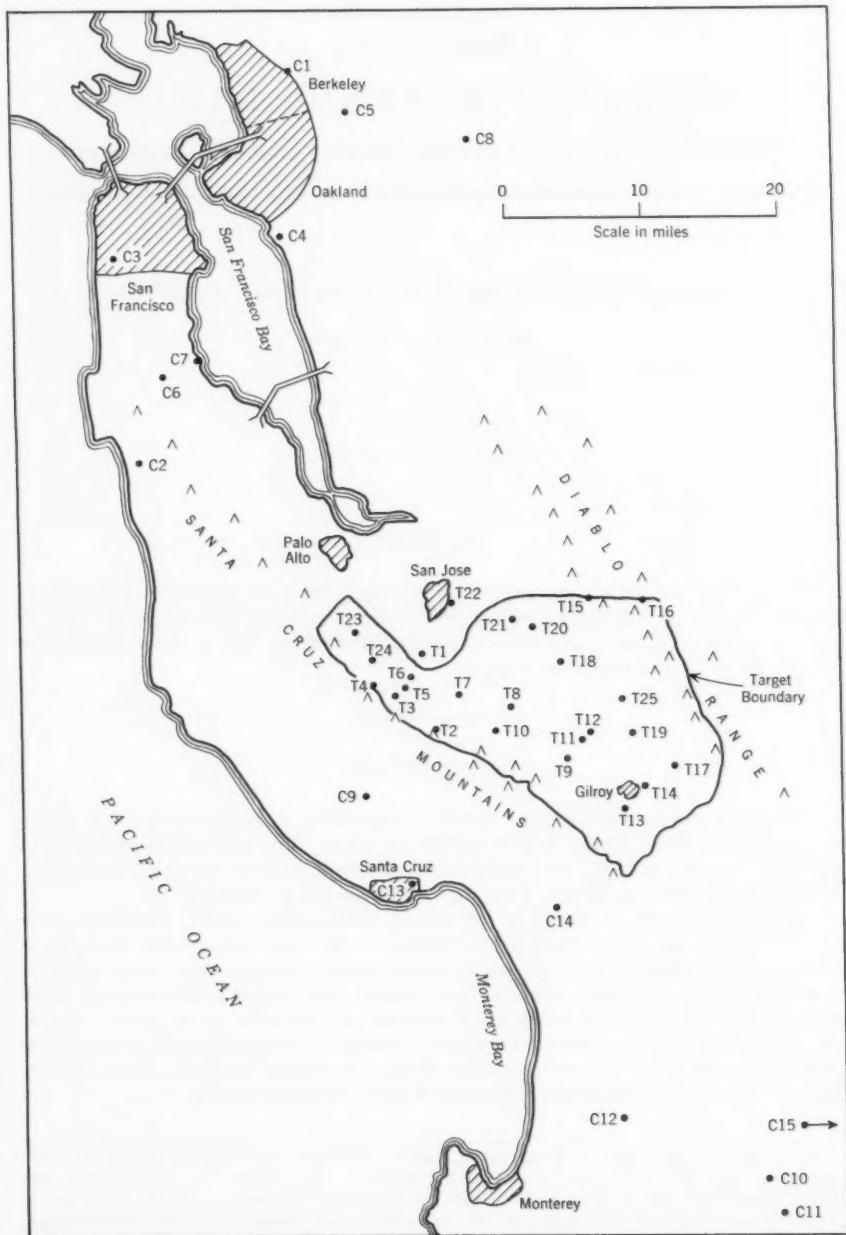


FIG. 1

The operational method used was the dispersal of silver iodide crystals from burners in which a solution of silver iodide and sodium iodide in acetone was burned in a propane flame. One burner was mounted on an aircraft for aerial seeding and the others located on the ground in and near the target area. In most storms, analysis of upper air conditions indicated enough instability to permit ascent of silver iodide crystals from the ground-based burners. In general, conditions during winter storms in the Santa Clara area conform to findings by Robert D. Elliott concerning those in Santa Barbara County.<sup>2</sup>

### CALCULATION OF REGRESSION EQUATION

In this paper an analysis is given of the results obtained during the 1955-56, 1957-58, and 1958-59 seasons. Data are employed from twenty five rain gauges within the target area and fifteen gauges outside the target area, these latter gauges being designated as control gauges. No control gauges were chosen to the northeast of the target area as these would be liable to contamination by silver iodide. The locations of the target gauges are identified in Fig. 1 by the letter T and the control gauges are identified by the letter C.

All control gauges are operated by the Weather Bureau, United States Department of the Interior (USWB), or by the San Francisco Water Department. The target records were obtained from the USWB, the Santa Clara Valley Water Conservation District, the San Jose Water Works, the San Francisco Water Department, and from private sources.

It is seen from Fig. 1 that the target gauges are not evenly distributed throughout the area. Thus a simple average of the rainfall at the twenty five gauges during any period would not be a satisfactory estimate of the average target rainfall for the period. To overcome this the Thiessen Method<sup>3</sup> of area weighting has been used. In this method it is assumed that the rainfall at any point in the area during any given period is the same as that observed at the closest target gauge during that period.

In this paper the target variable used will be the average target rainfall determined by the Thiessen Method, referred to hereafter simply as the target rainfall. The control variable will be the average of the rainfall observed at the control gauges. As a first step in the analysis it is necessary to examine the historical data from years when no seeding was done to establish a relationship between the target and control rainfall. As all seeding operations were limited to the months of December through March, the rainfall records used were for the period December 1 to March 31, inclusive for any given season. The base period used, extended from the 1944-45 winter to the 1953-54 winter, thus covering ten seasons. The target and control rainfall for each of these seasons is shown in Table 1.

In the following let  $Y$  be the target rainfall for any year,  $X$  be the control rainfall for any year and averages over the base period be denoted by bars. Let the variance of the target rainfall be denoted by  $V(X)$ . The target variance is computed according to

$$V(Y) = \frac{\sum_{i=1}^n (Y_i - \bar{Y})^2}{N-1} \dots \dots \dots (1)$$

<sup>2</sup> "California Storm Characteristics and Weather Modification," by Robert D. Elliott, *Journal of Meteorology*, Vol. 15, No. 6, Dec., 1958, pp. 486-493.

<sup>3</sup> "Precipitation Averages for Large Areas," by A. H. Thiessen, *Monthly Weather Review*, Vol. 39, 1911, pp. 1082-1084.

where N is the number of years in the sample (ten). A similar formula holds for the control variance  $V(X)$ . The standard deviation, S, for both target and

TABLE 1.—TARGET AND CONTROL RAINFALL FOR BASE PERIOD

Season, Dec. 1 to March 31	Control Rainfall, in inches	Target Rainfall, in inches
1944-45	14.41	15.02
1945-46	14.30	14.72
1946-47	8.65	8.83
1947-48	8.46	7.93
1948-49	17.00	16.77
1949-50	16.27	12.57
1950-51	14.66	13.99
1951-52	28.23	28.17
1952-53	15.48	15.55
1953-54	12.68	13.40

control rainfall is given by the square root of the variance. Substituting numerical values in the formulas.

$$\begin{aligned}\bar{X} &= 15.01 \text{ in.} & \bar{Y} &= 14.70 \text{ in.} \\ V(X) &= 30.03 \text{ in.}^2 & V(Y) &= 30.40 \text{ in.}^2 \\ S(X) &= 5.48 \text{ in.} & S(Y) &= 5.51 \text{ in.}\end{aligned}$$

The target and control rainfall for each year in the base period are shown on a scatter diagram in Fig. 2. The correlation coefficient is calculated according to

$$R(X Y) = \frac{\bar{X Y} - \bar{X} \bar{Y}}{S(X) S(Y)} \dots\dots\dots (2)$$

In this case  $R(X Y)$  is found to be 0.88. The formula for the best fit by the method of least squares is

$$Y(X) = \frac{S(Y)}{S(X)} R(X Y) (X + b) \dots\dots\dots (3)$$

where  $V(X)$  is the target rainfall as estimated from the control rainfall and b is a constant chosen so that

$$\bar{Y}(X) = \bar{Y} \dots\dots\dots (4)$$

In this case the equation simplifies to

$$Y(X) = 0.88X + 1.49 \text{ in.} \dots\dots\dots (5)$$

By means of this formula it is possible to estimate for any year when seeding was done what the rainfall would have been in the absence of seeding.

In order to establish confidence limits for the results, it is necessary to establish the standard error of estimate for the formula. As a start  $Y(X)$  was computed for each of the 10 yr in the base period. The variance of  $Y$  about  $Y(X)$  for the base period was then computed according to

$$V(Y/X) = \frac{\sum^n [Y - Y(X)]^2}{N - 2} \dots\dots\dots (6)$$

The use of  $(N-2)$  in the denominator rather than  $N$  is made necessary by the fact that two degrees of freedom were eliminated in determining the slope of the line and fixing  $\bar{Y}(X)$  equal to  $\bar{Y}$ . In this case the variance was found to be  $V(Y/X)$  equal 2.14 in.<sup>2</sup>

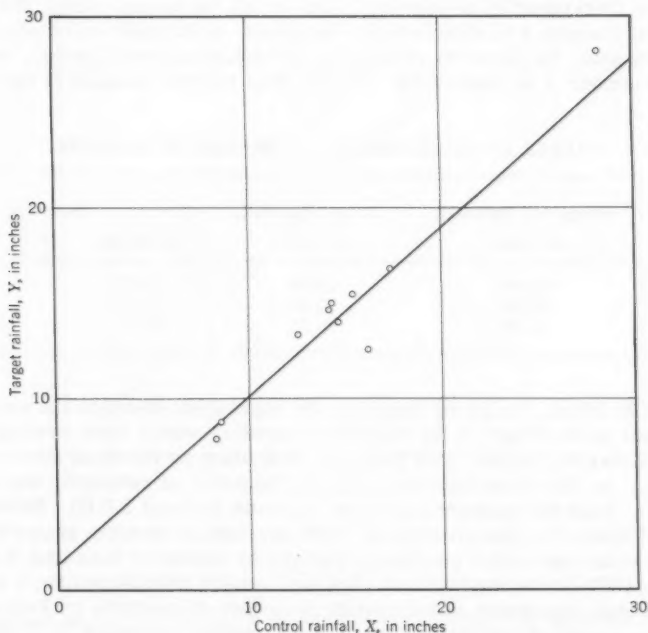


FIG. 2

If one were dealing with a long base period (say 50 yr) and a large number of seeded years, one could use the square root of  $V(Y/X)$  as the standard error of estimate. However, the base period is too short to allow this. The regression line drawn is only an estimate of the true regression line and the uncertainty is greatest for those years in which the rainfall departed markedly from the mean. A sufficiently accurate estimate of the variance of estimate for the average departure from the regression line over  $k$  years not included in the base period is

$$V(\bar{d}_k) + \frac{\sum [ (Y - Y(X)) ]^2}{N-2} \left[ \frac{1}{k} + \frac{1}{N} + \frac{(\bar{X}_k - \bar{X})^2}{\sum (\bar{X} - \bar{X})^2} \right] \dots \dots \dots (7)$$

while the distribution of the departures about the line is given by the Student *t* distribution with eight degrees of freedom.<sup>4</sup>

### CALCULATION OF RESULTS

The means are now available to determine how much additional rainfall was produced in the target area during the three seeded winters under consideration.

During the 1955-56 season seeding was discontinued for the whole target area from December 25 to January 3 and for all the target except the eastern hills from January 4 to February 9. However, to simplify calculations, consideration shall be given to results for the entire contract period, which ran from December 1 to March 15. During this period, rainfall at the controls

TABLE 2.—INCREASES DUE TO SEEDING BY SEASONS

Season	Predicted Rainfall,	Actual Rainfall,	Increase	
	in inches	in inches	in inches	% of Predicted
1955-56	24.05	29.05	5.00	21
1957-58	20.59	23.66	3.07	15
1958-59	12.69	16.27	3.58	28

averaged 25.64 in.; hence by applying the regression equation the estimate of the rainfall in the target in the absence of seeding would have averaged 24.05 in. The observed rainfall was 29.05 in., indicating an increase due to seeding of 5.00 in. In this case the value of *t*, or the error of estimate, was found to be 1.80 in. Thus the positive departure amounts to about 2.8 (*t*). Reference to a table of Student's *t* distribution for eight degrees of freedom shows the probability of obtaining such a positive departure by chance is less than 0.013.

During 1957-58 the whole target area was seeded from December 1 to March 15 except that operations on the northwest corner were ended on February 19. During the period of operations the control rainfall averaged 21.71 in., indicating a target rainfall without seeding of 20.59 in. The observed target rainfall of 23.66 in. exceeds this by 3.07 in., which in this case amounts to 1.8 (*t*). The probability of such a positive departure occurring by chance is approximately 0.06.

During 1958-59 the whole target area was seeded from December 1 to March 15. During this period the control rainfall was 12.73 in., indicating the target rainfall in the absence of seeding would have been 12.69. The observed target rainfall of 16.27 in. exceeds the expected value by 3.58 in., which in

<sup>4</sup> Final Report of Advisory Committee on Weather Control.

this case amounts to 2,3 (t). The probability of this positive departure occurring by chance is approximately 0.025.

The average apparent increase for the 3 yr is 3.88 in. By means of the formula the value of  $t$  for the average of the 3 yr is found to be 1.05 in. Thus the positive departure amounts to 3.7 (t). The probability of such a departure occurring by chance is less than 0.0025.

The results are shown for the 3 yr in Table 2 and the results are shown graphically in Fig. 3. The ten unseeded years are shown by crosses and the three seeded are shown by dated circles. It is seen that the three seeded years lie well above the regression line.

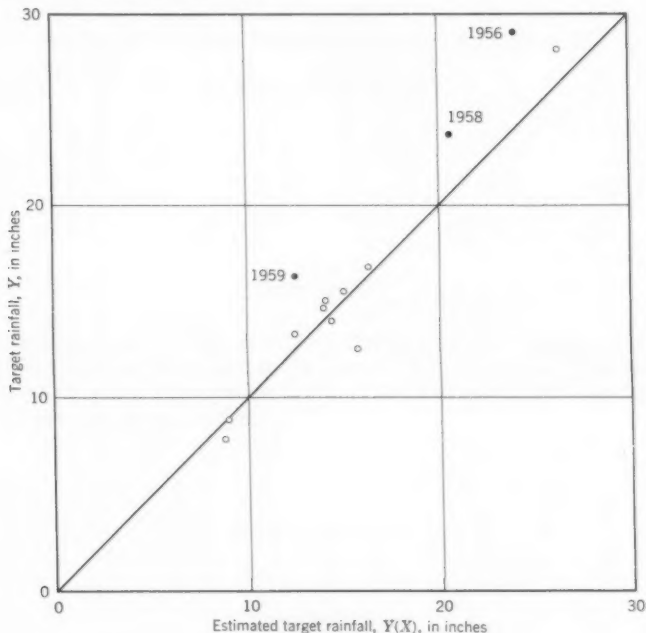


FIG. 3

### CONCLUSIONS

Increases in rainfall in parts of Santa Clara County designated as a target area for cloud-seeding have been demonstrated beyond any reasonable doubt, with the probability that some increase occurred being over 99.7%. The increases, computed on a seasonal basis, range from 15% to 28% of the expected rainfall. Over the 3 yr studied the additional rainfall is equivalent to an increase of 11.65 in. over the whole target area.

### ACKNOWLEDGMENTS

The writer wishes to express his appreciation to H. C. S. Thom of the USWB for advice on the statistics involved in the preparation of this paper.

The weather Modification Company of San Jose, Calif., conducted both the seeding and the evaluation described herein.



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Journal of the  
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ADVISORY COMMITTEE ON WEATHER CONTROL<sup>a</sup>

By Frederic A. Berry<sup>1</sup>

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SYNOPSIS

The investigations of the Advisory Committee on Weather Control are described, as well as the principal findings of the committee. The information obtained was of great importance to the field of atmospheric physics, and the science of weather modification.

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INTRODUCTION

The Advisory Committee on Weather Control was established by Act of Congress in December, 1953. Its membership comprised five prominent men from private life, the heads of five government departments (the Departments of Commerce, Defense, Interior, Agriculture, and Health, Education and Welfare) and the National Science Foundation. The committee was charged with making a "complete study and evaluation of public and private experiments in weather control for the purpose of determining the extent to which the United States should experiment with, engage in, or regulate activities designed to

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August, 1959 Weather Modification Conference in Denver, Colo.

<sup>1</sup> Aerometric Research, Inc., Goleta, Calif.

control weather conditions." The final report was due not later than June 30, 1956.

On July 1, 1954, the committee received its first appropriation and found itself equipped with a set of officers, a staff consisting of an executive secretary who was not a meteorologist, one stenographer, no authority to conduct research, and 2 yr to do the job, including 3 months lead time to get the final report through the Government Printing Office.

In retrospect, the only sensible thing to have done at this point would have been to immediately submit a final report saying that the job was impossible and resign in a body. However, having accepted the assignment, the committee set out to do the best possible under the circumstances. Upon the request of the Chairman, the Navy Department ordered the writer to duty with the committee, as the Chief Scientific Adviser in September, 1954.

Since the results of the experiments conducted by the various agencies of the government were being studied and evaluated by the agencies themselves, it was decided to concentrate the committee's limited resources on an attempt to evaluate the cloud-seeding projects, intended to augment precipitation, being conducted by various private organizations. The great majority of these projects used ground-based smoke generators emitting silver-iodide particles at the rate of  $10^{12}$  to  $10^{14}$  per sec, effective as ice-forming nuclei when measured at  $-20^{\circ}\text{C}$ .

The Committee sponsored a number of conferences attended by most individuals experienced in the various aspects of cloud physics and weather modification. Many valuable suggestions as to evaluation methods resulted; the one unanimous recommendation was that an attempt should be made to make a statistical evaluation of these cloud-seeding projects. It was realized that there would be many difficulties involved in using data not intended for this purpose, but the general feeling was that the quantity of the data would compensate to some extent for the quality.

Most meteorologists are somewhat sceptical of statistical analysis of meteorological data in the absence of an accepted valid physical theory. This is particularly true with respect to rainfall; natural variations under seemingly identical conditions may be larger than the effects which one is trying to identify. Furthermore, rainfall measurements are subject to considerable errors and the density of the rain gage networks is never sufficient to assure that the available data are representative of the area under study.

Accordingly, as a safeguard against ascribing a cause-effect relationship between increased rainfall and cloud-seeding, when it might be a natural variation, it was decided to conduct a series of small-scale field experiments, designed to test some of the assumptions on which the modern practice of cloud-seeding, to increase rainfall, is based. Some of these are as follows:

1. Do the normal atmospheric processes carry the silver-iodide particles from the surface to heights where the temperature and moisture conditions are suitable for them to be effective?
2. Do the silver-iodide crystals decay, that is change their crystalline structure as a result of photolytic action, at such a rate that they are ineffective even if they reach the proper altitudes in sufficient quantity?
3. Is it possible that the infusion of such vast numbers of particles into a cloud system will actually decrease rainfall by converting the entire cloud water content to ice particles?

After some delays, a two-phase program was inaugurated in January, 1955, a statistical evaluation program and a physical evaluation program. The statistical work will be studied subsequently.

### PHYSICAL EVALUATION

The first field program undertaken was in cooperation with the Mount Washington Observatory in New Hampshire. The observatory had been taking cloud-physics observations for a number of years, particularly ice-forming nuclei counts, liquid water content of clouds and cloud-drop size measurements. The purpose of the project was to determine whether or not silver-iodide particles released from ground generators, upwind of the mountain during the colder months of the year, would reach the summit in effective quantity. There thus was available, in effect, an instrumented target simulating conditions in the many upslope cloud-seeding projects in the western states. A total of 76 cloud-seeding operations was carried out between September, 1955, and June, 1956.

The results of the program can be summarized as follows:

a. Ground-based silver-iodide smoke generators can increase the concentration of ice-forming nuclei in the lower atmosphere, at distances up to 12 miles, by a significant amount;

b. present techniques appear to place the upper limit of nuclei concentrations so produced at approximately  $10^5$  particles per cu m, measured at  $-20^\circ\text{C}$ ;

c. "overseeding," the flooding with ice-forming nuclei of supercooled clouds capable of producing appreciable precipitation, does not appear to be possible with presently used equipment and techniques; and

d. silver-iodide nuclei produced by the propane-acetone method have a decay rate to something less than two orders of magnitude per 30 min exposure time at a temperature of  $-15^\circ\text{C}$ . It thus appears that deactivation of the nuclei is not a matter of practical concern.

In the summer of 1955, a study was initiated to check the motion of silver-iodide crystals and their rate of deactivation under warm summer conditions. The silver-iodide was released from ground generators and hunted with equipment mounted on a sailplane. Tests were conducted in the vicinity of Missoula, Mont., and the work was continued later that year in California, using a light airplane. The latter technique as developed during this study was used on practically all the later field projects sponsored by the Advisory Committee.

During the summers of 1953, 1954, and 1955, a cooperative program of observing and charting thunderstorm and other cloud systems from a network of 22 observing stations, manned by trained observers, had been in progress in the Northwest with headquarters at Missoula. In the summers of 1956 and 1957, the committee supported a program of cloud-seeding studies in the area. A mobile radar unit was placed on a mountain summit and silver-iodide generators were placed on nearby roads. Two light planes were used to collect detailed information on cloud positions and characteristics, to measure the concentrations of ice-forming nuclei, and occasionally to seed with dry-ice or

silver-iodide. Camera equipment was located at the radar site and the control point on a nearby summit to record cloud-seeding effects wherever possible.

Another study program was undertaken during the summers of 1956 and 1957, at Boca Raton, Fla. A line of towering cumulus clouds builds up along the coast practically every day during the summer months, in practically the same position. It was thought that this would present an excellent opportunity to observe the effects of seeding on cumulus clouds downwind from the generators, while unaffected clouds would be on either side of the seeded ones. As far as this particular result was concerned the project was a failure. However, a careful study of the time-lapse motion pictures taken every day resulted in the formulation of a theory concerning the initiation of precipitation in cumulus clouds which is a major contribution to cloud physics. Knowing the temperature of the cloud-base and the ascent velocity of the cloud towers it is possible to predict with some accuracy whether precipitation in the cloud will be initiated by the water process (the so-called warm-cloud type) or the ice-crystal process. The theory was tested in other areas and found to work satisfactorily.

One of the most frustrating aspects of the evaluation program was the wide variety of results reported by various investigators in the measurement of natural ice-nuclei, as reported in the fragmentary data available. The committee was fortunate in being able to assemble a group of interested scientists who had been making measurements in a variety of differing techniques at Pasadena, Calif. in May, 1957. Actual measurements with the various types of equipment indicated that the differences between instruments were considerably less than one would believe from the published material. The exchange of ideas and technical information resulting from this conference has led to a more uniform and useful exchange of data between the people involved.

*Santa Barbara Project.*—Although a considerable fraction of the western United States, as well as some areas in the Midwest and East have been the site of cloud-seeding operations since 1950, using ground-based silver-iodide generators, it was not until January, 1957 that a research program was established, specifically designed with the necessary scientific control and extensive instrumentation, to test the efficacy of this method. The participants in this program, which is an outstanding example of how various groups with different but associated interests, can pool their limited resources to the benefit of all, are the:

County of Santa Barbara  
Statistical Laboratory of the University of California  
Department of Water Resources of the State of California  
National Science Foundation  
United States Weather Bureau  
United States Forest Service  
North American Weather Consultants  
Advisory Committee on Weather Control (during the first year)

The sponsorship by the Advisory Committee of the various small and relatively inexpensive projects briefly reported in the foregoing summary yielded information of basic importance to atmospheric physics. At the same time it permitted the committee to proceed in its task with a reasonable degree of assurance that the effects observed were more than random fluctuations of completely natural precipitation.

## STATISTICAL EVALUATION

The writer's brief work with the Advisory Committee served to strengthen the opinion that most, if not all, statistical treatment of meteorological data is done by meteorologists who know little of statistics, or by statisticians who know absolutely nothing about meteorology. The Advisory Committee, however, was extremely fortunate in obtaining the services of a man who knows a great deal about both, Herbert Thom.

The results of the work of Mr. Thom's group are not spectacular in the newspaper sense, but represent a milestone in the attempts to solve this particular problem. Given below is a quotation from the committee's final report:

"1. For the orographic and semi-orographic projects--all of which were on the West Coast--evidence indicates that cloud-seeding produced an average increase of 10 to 15 percent from seeded storms. The evidence supporting this conclusion is impressive for a number of reasons:

a. The conclusion was the result of an impartial approach to the problem of the evaluation of the effect of cloud-seeding on precipitation.

b. The conclusion was the result of testing procedures shown to be highly sensitive in detecting increases in precipitation on the large quantity of data available for evaluation.

c. The 299 storms evaluated represent, for most of the projects, the entire seeding program beginning with the earliest operations conducted in the areas and continuing through those which were in operation at the time the evaluations were made.

d. The estimated increase in precipitation based on the regression analysis agrees very closely with what has been independently predicted from basic meteorological principles applied to such geographical areas as make up the project sites of these operations.

e. Statistical calculations on the data result in very heavy odds that the average increases found are not attributable to natural variability in the precipitation.

2. For the non-orographic projects, the same procedures and testing methods did not detect any change in the precipitation that could be attributed to cloud-seeding.

But, the fact that no increase in precipitation was detected does not warrant the conclusion that there was no increase -- the increase may have been too slight to measure by the statistical methods used. In these areas analytical difficulties are multiplied by the complicated rainfall processes in contrast to the comparatively simple West Coast rainfall processes.

3. A third important conclusion is that no evidence was found, in any project intended to increase precipitation, which suggested cloud-seeding had produced a negative effect."

The final quote from the Committee's report states:

"The importance of vigorous attack on the problems in this field can hardly be overemphasized. Few areas of science have implications so profound to all mankind as the study of the atmosphere and the phenomena which occur in it."



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Journal of the  
IRRIGATION AND DRAINAGE DIVISION  
Proceedings of the American Society of Civil Engineers

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THE NATURE OF CLOUD SYSTEMS<sup>a</sup>

By Horace R. Byers<sup>1</sup>

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SYNOPSIS

Cloud systems suitable for modification by seeding are discussed. The mechanisms of precipitation formation and results obtained from seeding various types of clouds are briefly considered.

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It might be well for meteorologists to take stock at this time of the weather systems with which they hope to deal in modification attempts. They are only trying to increase the precipitation efficiency of mechanisms that nature already provides, so one must always be aware of the available types of rain-generating cloud systems of any particular region or season under consideration.

In the first place, it is unnecessary to present data to prove that in periods of drought there is always a remarkable lack of clouds or cloud systems suitable for treatment; in fact, droughts are usually characterized by long, monotonous periods of virtually cloudless skies. Those hapless farmers who, after weeks and weeks of searing drought, pray for rain, perhaps had best make their supplications more modest and ask for a few suitable clouds, on the theory that God helps those who help themselves.

What are suitable clouds; when, where and under what circumstances do they occur? Other papers have given partial answers through examples of

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August, 1959 Weather Modification Conference in Denver, Colo.

<sup>1</sup> Department of Meteorology, The University of Chicago, Chicago, Ill.

clouds studied or treated in several different geographical regions. It should be emphasized that man can supplement natural precipitation only through the temperature ranges where natural airborne particles are inactive as ice-nucleating agents— $0^{\circ}$  C to  $-15^{\circ}$  C or  $-20^{\circ}$  C, or perhaps colder in extreme cases. For water-spray stimulation of clouds that are warmer than freezing, another set of variables must be taken into account; however, as usual, meteorologists are mainly concerned with the ice nucleating mechanism.

In their classical paper<sup>2</sup> J. Bjerknes and H. Solbert summarized newly acquired knowledge by pointing out that rain-producing clouds can be formed only through the adiabatic cooling with expansion of air, and that this expansion must come about as a result of upward motion. Their model of a middle-latitude rainstorm required gradual ascending motion above a warm front and an upward push of air by the advancing wedge of a cold front. This type of system roughly approximates the storms in most of the United States in the cooler half of the year. R. D. Elliott illustrates<sup>3</sup> how the air-flow and cloud formations are distributed with respect to the cold or occluded front in rain situations on the California coast. In a typical midwinter storm in the Santa Barbara area, the freezing line is between 1.5 km and 3 km. (roughly 5,000 ft to 10,000 ft). One might suggest that this temperature condition is characteristic of storms in the eastern two-thirds of the United States in the spring or fall, but at those seasons it is more likely that summer conditions will occur ahead of the cold front and winter conditions behind it. F. Hall has reported on work on winter storms of western Washington.<sup>4</sup>

There are other types of clouds with precipitation potential which may not be directly associated with major disturbances. Among these are so-called orographic clouds or, more simply, clouds formed over mountains, whether due to orographic upward forcing of the wind or to the effect of these high-level heat sources, in summer, in accentuating convection. Stable cloud forms are characteristic of the mountains in the cool season or in the presence of an extensive snow cover. These are clouds that may form arcs over the mountains at various levels with intermittent precipitation from the lower forms. If they happen to be in the right range of temperatures they are quite suitable for artificial seeding, but in many cases they are accompanied by overlying precipitating cirrus forms which produce natural seeding. They often have wave clouds downwind from the mountains which are sometimes right for seeding. F. H. Ludlam has worked with stable mountain clouds in Sweden.<sup>5</sup>

The unstable mountain clouds of summer have been discussed elsewhere. They are clouds with rapid vertical growth, under favorable conditions, and they may develop into thunderstorms. In summer, in most locations, in the United States, the freezing line is at 3.5 km to 4.7 km above sea level (roughly 11,500 ft to 15,500 ft). They appear to be promising clouds to be seeded with silver iodide from aircraft.

<sup>2</sup> "Meteorological Conditions for the Formation of Rain," by J. Bjerknes and H. Solberg, *Geofysiske Publikationer*, vol. 2, No. 3., 1921.

<sup>3</sup> "California Storm Characteristics and Weather Modification," by R. D. Elliott, *J. Met.*, vol. 15, 1958, pp. 486-493.

<sup>4</sup> "The Weather Bureau ACN Project," by F. Hall, *Amer. Meteorological Soc., Met. Monographs*, vol. 2, No. 11, 1957, pp. 24-46.

<sup>5</sup> "Artificial Snowfall from Mountain Clouds," by F. H. Ludlam, *Tellus*, vol. 7, 1955, pp. 277-289.

An interesting type of convective cloud is the trade-wind cumulus. Every day there are literally millions of these clouds in the undisturbed regions of the tropical oceans in the belt of the trade winds. They are probably the smallest known clouds capable of producing precipitation; they can do so when they have a vertical depth of only 5,000 ft or 6,000 ft and a diameter of less than 1 mile. Of course the amounts of precipitation from them, in this stage, cannot be very great, but they can develop into larger cumuli, which produce ample rains. In these tropical regions, the first precipitation to fall out of a cumulus cloud is initiated at temperatures warmer than freezing. Treatment by water spray to start the growth of raindrops by coalescence has proved successful in initiating rain out of trade-wind cumuli that were too weak to produce rain without such help. The successful work with the trade-wind cumuli was carried out by the University of Chicago group in the Caribbean area.<sup>6</sup>

Finally we come to that all-too-familiar, yet poorly understood, continental cumulus, characteristic of the summer season throughout North America, from the Rocky Mountains to the Atlantic and from the Arctic to the Gulf of Mexico. Typically, it builds up through 15,000 ft or more (base at 5,000 ft, top at 20,000 ft or more) before initiating precipitation. On the other hand, it can sometimes initiate rain by an all-liquid process before it reaches the freezing level, much like its little brother of the tropical oceans. These clouds are similar to the unstable cumulus of the mountain areas, as far as size and height of the freezing level goes, but their bases are 5,000 ft to 10,000 ft lower. They are ultimately responsible for nearly all the rain of the growing season, in this vast area of North America, representing the precursors of thunderstorms, squall lines and, occasionally, hail and tornadoes.

Seeding of the continental cumulus has been tried, but, curiously enough, the commercial projects have not been properly organized to provide a test and the scientific ones have, up to now, lacked sufficient financial support to carry the work through, to a logical conclusion. This is the task we have set before ourselves at the University of Chicago.

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<sup>6</sup> "Artificial Nucleation of Cumulus Clouds," by R. R. Braham, L. J. Battan and H. R. Byers, Amer. Meteorological Soc., Met. Monographs, vol. 2, No. 11, 1957, pp. 47-85.



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PHYSICAL PROPERTIES OF CLOUDS<sup>a</sup>

By Roscoe R. Braham, Jr.<sup>1</sup>

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SYNOPSIS

To form an idea of the difficulties in evaluating cloud-seeding effects, the problem can be considered comparable to the study of human genetics.

In the past most seeding effects were indicated by straightforward statistical evaluations. Now more tests are being conducted which are popularly called "physical evaluations." Nine of these physical evaluations are presented in this paper.

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INTRODUCTION

Meteorological studies have long been hampered by a number of difficulties characterizing the geophysical sciences. Among the more important of these are:

- a. Inability to duplicate atmospheric conditions within the laboratory;
- b. Inability to completely specify the initial and final conditions of any particular experiment or study;
- c. Lack of control of initial conditions;
- d. Great variability of natural atmospheric conditions; and
- e. Inadequacy of the tools with which to attack the more important problems.

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<sup>a</sup> Presented at the August, 1959 Weather Modification Conference in Denver, Colo.

<sup>1</sup> Department of Meteorology, The University of Chicago, Chicago, Ill.

Cloud-seeding studies have been particularly hard to evaluate, for in addition to these difficulties which surround all meteorological studies, we must add

- f. The seeding effects which are to be studied may be small, compared with natural variations in the atmosphere.

Human genetics appears to be the only other area of comparable difficulty within the physical and biological sciences. There too, these six conditions make life troublesome for the scientists. Reflecting on the controversies and differences of opinion which seem to characterize writings in that area, meteorologists can take refuge in the fact that others are also having trouble evaluating experiments and estimating the ultimate outcome of continued experimentation. In fact, it appears that meteorologists have the easier task and have made the greater headway.

Analysis of cloud-seeding experiments in the past has followed a few relatively simple lines. The test variable usually has been the amount of rain or snow collected in some sort of a gaging system on the ground. Customarily one compares the amount of rain (snow) falling in a target area, or during a target period, with the amount which falls on a control area or during a control period. Provided the target-control areas (periods) are selected with adequate precaution, and provided the tests are sufficiently numerous, this method of analysis is capable of finding seeding effects regardless of how large or small these effects might be. Unfortunately, however, experience has shown that proper selection of target-control areas (periods) is difficult, while at the same time natural variability of precipitation is large compared with artificially induced changes resulting from present-day seeding techniques. As a result, few seeding experiments have provided more than personal opinions as to the results of cloud-seeding.

Although in a few cases the straightforward statistical test has indicated effects ascribable to seeding, this method of analysis cannot be expected to provide clues as to the way in which such effects were produced, and therefore is inherently of limited value.

In spite of the fact that past experiments have not provided clear-cut answers to the question of cloud-seeding, the immense economic value of a successful weather-modification technique and the pressures resulting from widespread seeding activities have prompted meteorologists to study carefully the processes by which natural precipitation is produced. Theoretical studies of precipitation processes have been carried out by T. Bergeron,<sup>2</sup> Houghton, E. G. Bowen,<sup>3</sup> B. J. Mason and F. H. Ludlum,<sup>4</sup> T. W. R. East,<sup>5</sup> T. B. Todd,<sup>6</sup> and many others. Compared with the number and quality of theoretical studies, field measurements of conditions accompanying the formation of precipitation in clouds are rare indeed.

The most extensive set of measurements of precipitation formation in stratus clouds was carried out by R. M. Cunningham.<sup>7</sup> Studies of cumulus clouds are

<sup>2</sup> "On the Physics of Clouds and Precipitation," by T. Bergeron, Proc. Intern. Union of Geodesy and Geophysics, 5th Assembly, Lisbon, 1935, part 2, pp. 156-178.

<sup>3</sup> "Formation of Rain by Coalescence," by E. G. Bowen, Aust. J. Sci. Res., 1950, 3, Ser. A., pp. 193-213.

<sup>4</sup> "The Microphysics of Clouds," by B. J. Mason and F. H. Ludlum, Rep. Progress Phys., 1951, 14, pp. 147-195.

<sup>5</sup> "An Inherent Precipitation Mechanism in Cumulus Clouds," by T. W. R. East, Q. J. Roy. Met. Soc., 1957, 83, pp. 61-76.

<sup>6</sup> "Cumulus Studies," by T. B. Todd, Final Report of the Advisory Committee on Weather Control, 1957, vol. II, pp. 151-161.

<sup>7</sup> "The Distribution and Growth of Hydrometeors Around a Deep Cyclone," by R. M. Cunningham, M. I. T. Weather Radar Tech. Report No. 18., 1952.

many more numerous; those of H. K. Weickmann and H. J. aufm Kampe,<sup>8</sup> R. R. Braham, S. E. Reynolds and H. J. Harrell, Jr.,<sup>9</sup> H. R. Byers and R. K. Hall,<sup>10</sup> and Braham, L. J. Battan and Byers<sup>11</sup> are representative of some of the more comprehensive of these studies.

As a result of these many and varied studies, the natural precipitation mechanisms are fairly well understood in general, if not in detail. A summary of this knowledge is presented in Fig. 1. It is a little unfortunate that the majority of the studies thus far have involved cumulus cloud rain. Although the basic physics of rain formation in stratus and cumulus clouds is similar, undoubtedly the differences in cloud duration and updraft speeds make substantial differences in details of the processes. In defense of the emphasis of the work on cumuli, however, it should be pointed out that substantially all of the precipitation which falls in the summer months in the United States comes from cumulus clouds.

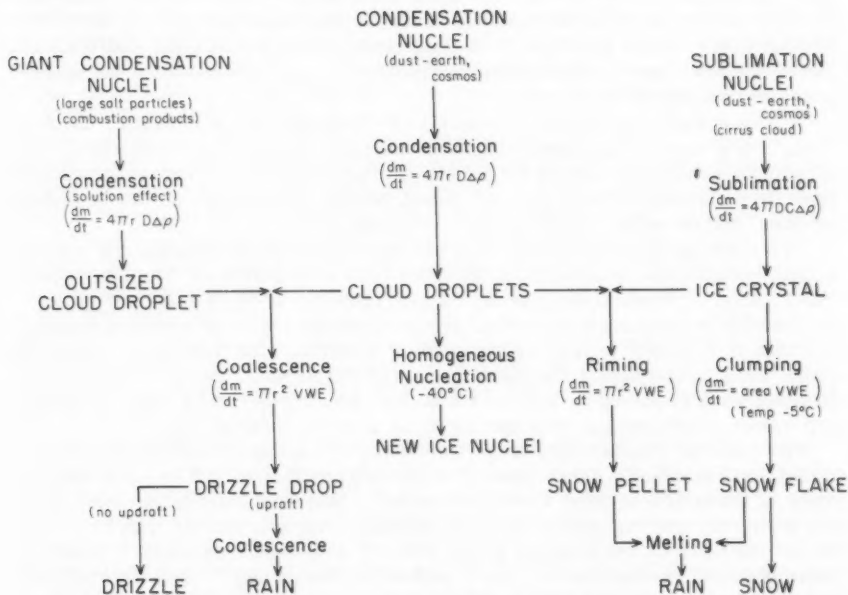


FIG. 1.—SCHEMATIC OUTLINE OF THE MAJOR PROCESSES OF THE FORMATION OF PRECIPITATION (AFTER MASON).

<sup>8</sup> "Physical Properties of Cumulus Clouds," by H. K. Weickmann, and H. J. aufm Kampe, *J. Meteor.*, 1953, 10, pp. 204-211.

<sup>9</sup> "Possibilities for Cloud-seeding as Determined by a Study of Cloud Height Versus Precipitation," by R. R. Braham, Jr., S. E. Reynolds and J. H. Harrell, Jr., *J. Meteor.*, 1951, 8, pp. 416-418.

<sup>10</sup> 1955: "A Census of Cumulus Cloud Height Versus Precipitation in the Vicinity of Puerto Rico During the Winter and Spring of 1953-54," by H. R. Byers and R. K. Hall, *J. Meteor.*, 1955, 12, pp. 176-178.

<sup>11</sup> "Artificial Nucleation of Cumulus Clouds," by R. R. Braham, Jr., L. J. Battan and H. R. Byers, *Meteorological Monographs*, 1957, 2, 11, pp. 47-85.

Through a knowledge of the natural rain mechanisms it has been possible to devise seeding-evaluation techniques which are more powerful than the simple statistical tests of rain on target versus control area used heretofore. Providing one designs the experiments properly and measures the pertinent cloud and precipitation variables, one can examine every step in the precipitation mechanisms for hypothesized seeding effects. In this way one has the hope of establishing the "how and why" of seeding effects. Such studies have the further advantage of reducing the problem to a series of cause and effect relationships, each of which can be examined independently. In this way, one can trace the role of seeding through each step in the development of rain. In principle, one can thereby more easily detect small seeding effects. In addition, such studies may permit the development of improved seeding technology.

Such studies are popularly, though unfortunately, called "physical evaluations" in contrast to the "statistical evaluations" previously used in cloud-seeding studies. Although the contrast in emphasis is desirable, it is improper to suggest that physical evaluations make no use of statistics. Of necessity, almost every kind of physical evaluation requires the use of good statistics for the design of experiments, testing of hypotheses, and estimation of the magnitudes of demonstrated effects.

A wide range of physical evaluations of cloud-seeding is possible. Each of them rests upon a hypothesis of some change, in response to seeding, of a measurable characteristic of the clouds or cloud-systems. Several such studies have been carried out both on cold clouds, seeded with dry ice or silver-iodide smokes, and on warm clouds seeded with water.

The construction, by Todd,<sup>6</sup> of a physical model for computing the time at which precipitation would emerge from the base of cumuli over Florida, constituted a kind of physical evaluation. So also does the work of J. Spar<sup>12</sup> on Project Scud in attempting to associate pressure changes with widespread seeding, and that of F. Hall<sup>13</sup> in tagging the seeding material with fluorescent pigments which were subsequently identified in rain at the ground. Many aspects of the Arizona work reported by Battan<sup>14</sup> also may be considered as seeking cause-and-effect relationships, thus qualifying as physical evaluations.

The cumulus cloud studies at the University of Chicago, Cloud Physics Laboratory have involved a large number of physical evaluations of seeding effects. Many of these are similar to studies made by other organizations, but others are unique for the reason that the careful inflight measurements which characterize the work of the Chicago group are not available elsewhere. Some of these physical evaluations will be discussed subsequently. In every case the key to success is to take data in such a way as to obtain a valid control group against which to judge the data obtained in the seeded group.

#### EXAMPLES OF PHYSICAL EVALUATIONS

*Frequency of Precipitation Development.*—One of the most obvious ways of checking the efficacy of cloud-seeding is to examine the seeded clouds for the formation of precipitation. Provided one has a good, nonsubjective way for

<sup>12</sup> "Project Scud," by J. Spar, Meteorological Monographs, 1957, 2, 11, pp. 5-23.

<sup>13</sup> "The Weather Bureau ACN Project," by F. Hall, Meteorological Monographs, 1957, 2, 11, pp. 24-46.

<sup>14</sup> "Effects of Silver-iodide Seeding on Orographic Cumuli," by L. J. Battan, Paper presented before National Meeting, Amer. Meteorological Soc., New York City, Jan. 29, 1959.

identifying the precipitation, and provided the data are properly randomized, this is one of the easiest ways to observe effects of seeding. In some cumulus clouds were selected in pairs. Through a random process one of the pair was selected for seeding. The formation of precipitation was observed by means of a carefully calibrated airborne radar. Analysis consisted of comparing the frequency of formation of precipitation echoes in the seeded and unseeded clouds. Such an analysis proved beyond doubt that water seeding in warm cumuli initiated rain in clouds wherein it would not have formed naturally.

Although this is one of the easiest of all physical evaluations, it is absolutely essential that the investigator have a way of instrumentally detecting the formation of precipitation. The visual appearance of the cloud is entirely inadequate and studies based upon such data are suspect.

*Time Required for Precipitation Formation.*—Another excellent way of verifying results from water seeding is through a study of the average time required for the development of precipitation. Unlike silver-iodide seeding, water seeding bypasses several steps in the natural precipitation process. Thus it is possible for rain to form much earlier in water-seeded clouds than in clouds which have not been seeded. This difference can be tested by means of Wilcoxon ranking test as described by W. H. Kruskal and A. W. Wallis.<sup>15</sup>

*Level (Temperature) of Region of First Precipitation.*—Cold-box studies of natural ice-nuclei show that the atmosphere usually contains very few ice-nuclei effective at temperatures warmer than about  $-20^{\circ}\text{C}$ . At temperatures only slightly colder than  $-20^{\circ}\text{C}$  the atmosphere usually contains adequate numbers of ice-nuclei for precipitation formation (although many cumulus clouds do not last long enough for these nuclei to become effective). The threshold temperature for silver-iodide smokes is in the vicinity of  $-4^{\circ}\text{C}$ . Much of cloud-seeding is based on the premise that proper seeding of clouds with silver-iodide smokes will bring about the nucleation of the water contained in the  $-4^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$  region. The extent to which this is true in cumuli can be checked by the simple expedient of observing the heights of formation of the first precipitation echoes by means of suitable radar. The paper by Battan<sup>16</sup> is an example of such a use of radar.

*Minimum (and Average) Dimensions of Cloud Required for Precipitation Development.*—Even though one might succeed in initiating the precipitation process in a cloud, rain will not fall from it unless the small, newly formed, precipitation particles can grow by collision and coalescence with cloud-droplets. Thus there are minimum cloud dimensions (depth and liquid water content) required for precipitation development and one can expect that these values will be different for seeded and unseeded clouds. Such a hypothesis is capable of test, both by comparison between seeded and unseeded clouds in the field, and by theoretical study. Since the terminal speed and collision-coalescence efficiencies of drops are essentially functions only of their size, it is possible to compute the distance through which a drop must fall in growing to any given larger size. Table 1 gives this distance for clouds of 1 and 3 g per cu m cloud water content.<sup>17</sup> The smaller value is probably representative of most cumulus clouds. The larger value will be found only in isolated cores of large cumu-

<sup>15</sup> "Use of Ranks in One-criterion Variance Analysis," by W. H. Kruskal and A. W. Wallis, J. Amer. Stat. Assn., 1952, 47, pp. 583-621.

<sup>16</sup> "Experiments on Treatment of Summer Cumulus Clouds in Arizona," by L. J. Battan and A. R. Kassander, Paper presented before Joint Conference, ASCE and Amer. Meteorological Soc., Denver, Colo., Aug. 27, 1959.

<sup>17</sup> "How Does a Raindrop Grow?," by R. R. Braham, Jr., Science, 1959, 129, pp. 123-129.

li, whereas stratified clouds have water contents less than 1 g per cu m. Table 2 shows the effect of cloud-size on the results of water seeding of cumulus clouds. Note that the computed values compare favorably with field measurements, in that only clouds in excess of 4,000 ft thickness produced precipitation following seeding.

*Position, Relative to Height of Seeding Plane, of First Precipitation.*—In the case of seeding experiments using an airplane to place seeding materials directly in the clouds, a meaningful physical evaluation is to compare the level, relative to the seeding altitude, of precipitation formation in seeded and unseeded clouds. For example, in the case of water-seeding in tropical clouds it was found<sup>18</sup> that echoes in seeded clouds always formed below the seeding plane. Based upon the physics involved, this finding furnished very satisfactory evidence of the effects of the seeding.

*Minimum Thermal Energy Required for Precipitation Development.*—A Very important aspect of seeding analysis concerns the possibility that seeding will cause rain in clouds having insufficient vigor to rain naturally. The intensity of the convection process is directly governed by the buoyancy of the cloud air. This in turn is measured by the temperature difference between the cloud and its environment. Therefore it is possible to make allowance for the varying

TABLE 1.—APPROXIMATE FALL DISTANCES AND TIME REQUIRED FOR GROWTH OF DROPS OF INITIAL  $25\mu$  RADIUS IN A UNIFORM CLOUD OF DROPLETS OF  $10\mu$  RADIUS.

Drop radius, in microns	Water Content			
	1 g per cu m		3 g per cu m	
	Fall distance, in feet	Fall time, in minutes	Fall distance, in feet	Fall time, in minutes
25	0	0	0	0
50	500	24	200	8
100	1,640	40	540	13
250 (rain)	4,400	48	1,470	16
500	8,300	55	2,700	18

degrees of vigor of the seeded and unseeded clouds, provided one makes careful measurements of the air temperatures in and around the clouds being studied. A very important analysis of this kind was carried out by B. Ackerman<sup>19</sup> who showed that water-seeding of positively buoyant clouds did not increase the probability of precipitation formation. However, seeding did increase the likelihood that negatively buoyant clouds would develop precipitation. This is interpreted to mean that positively buoyant clouds usually contained enough vigor (also related to size, duration) to develop rain through natural mechanisms. However, seeding produced rain in weak clouds lacking the capability for natural rain.

*Relative Concentration of Liquid and Solid Precipitation Forms as a Function of Height (Temperature).*—Since the hypothesized action of silver-iodide smokes is to convert a portion of the subcooled cloud to ice-crystals, an obvious physical evaluation is to compare the relative amounts of liquid water and ice at various levels within the seeded and unseeded clouds. Unfortunately, this isn't

<sup>18</sup> "On the Formation of Precipitation in Tropical Cumulus," by J. Sievers, M. S. Thesis submitted to Dept. of Meteorology, Univ. of Chicago, 1955, 24 pp.

<sup>19</sup> "Buoyancy and Precipitation in Tropical Cumuli," by B. Ackerman, J. Meteor., 1956, 13, pp. 302-310.

a very sensitive test, except in the instance where the desired action is over-seeding, for the reason that a relatively very small number of ice-crystals may be sufficient for effective seeding. This test procedure has merit, however, in assisting the scientist in sorting out the relative role of the ice-crystal mechanism and the condensation-coalescence mechanism of rain formation. This is a problem of considerable difficulty in the analysis of cloud-seeding experiments. Radar has proven very useful for assessing cloud-seeding results, but unfortunately it cannot distinguish between echoes formed through the all-water process and those formed through ice-crystals. Thus the scientist investigating silver-iodide seeding may be led astray by the echoes which form by the all-water mechanism in the silver-iodide-seeded clouds. Only through collecting samples of the precipitation particles can one distinguish between these two processes and thereby assess the role of the silver-iodide in inducing precipitation.

*Total Duration of Cloud Life.*—There are several factors which tend to limit the life of a cloud. One of the most important is the vigor of the initial updraft. Other considerations are the environment humidity, wind speed and shear, and the development of precipitation. It has been argued that the increased release

TABLE 2.—EFFECT OF LARGE VALVE TREATMENT OF TROPICAL CUMULI AS A FUNCTION OF CLOUD DEPTH BELOW TREATMENT LEVEL. (CLOUD BASE ASSUMED AT 2,000 FT)

Cloud thickness, in hundreds of feet	Number of Clouds				Percentage of clouds with echoes		
	Untreated		Treated		Untreated	Treated	Census
	Echo	No echo	Echo	No echo			
30 to 39	0	0	0	1	0	0	0
40 to 49	0	5	3	3	0	50	4
50 to 59	5	12	5	7	29	42	12
60 to 69	2	13	9	9	13	50	26
70 to 79	2	3	3	2	40	60	50
80 to 89	1	1	1	1	50	50	75

of latent heat of fusion from silver-iodide or dry-ice seeding will increase the buoyancy of the cloud air and thus cause it to develop to greater ultimate size, and consequently to a greater total life duration. It is also known, however, that the development of precipitation places a very effective brake on the further development of cumulus clouds. Therefore, it is difficult to predict the effect of dry-ice or silver-iodide seeding on cloud duration. A study by Braham<sup>20</sup> found no detectable differences in the duration of dry-ice-seeded cumulus clouds and unseeded clouds of similar characteristics. It did show, however, that the short lifetimes of cumuli make them difficult targets for weather modification studies. For example, in Fig. 2 is plotted the frequency distribution of cumulus clouds of various durations. Fig. 2 also shows the probability of natural precipitation development as a function of cloud duration. For this purpose duration is defined as the total life of the cloud beyond the time its top reached the  $-5^{\circ}$  C level. Thus, if one accepts 800 sec at a temperature of  $-5^{\circ}$  C (or colder) as required for a silver-iodide particle to grow into a precipitation particle, it is found from Fig. 2 that only 40% of the clouds will last

<sup>20</sup> "Cloud Duration as an Important Parameter in Cumulus Cloud-seeding," Paper presented before National Meeting, Amer. Meteorological Soc., Washington, D. C., May 7, 1958.

long enough, and of these about 55% will develop precipitation through natural causes. Data for Fig. 2 were obtained in Illinois, Missouri, Arkansas, Kansas, and Arizona during summer months.

*Rate of Growth and Total Size Reached by Precipitation Regions Inside of Clouds.*—Just as radar can be used to detect the initial appearance of precipitation within a cloud, it may also be used to measure the size and rate of growth to these precipitation regions. Although this test has not been used very effectively thus far, it is capable of providing a great amount of information relative to seeding effects. Of all the physical evaluations, this one comes closest to measuring the quantity of greatest importance to the client, that is, the amount of water on the ground. It has the advantage, moreover, of providing data on every seeded cloud, and not only the ones which happen to be located over a surface rain gage. This use of radar should be exploited by scientists interested in the cloud-seeding problem.

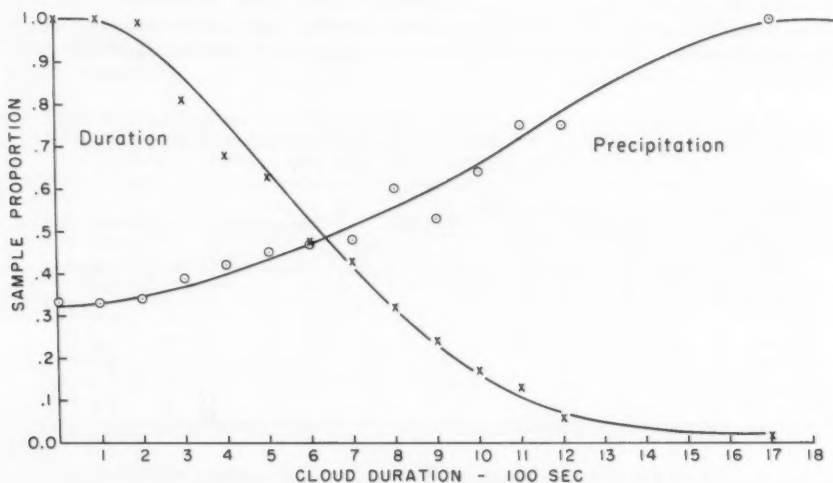


FIG. 2.—PROBABILITY OF NATURAL PRECIPITATION DEVELOPMENT IN CUMULUS CLOUDS AS A FUNCTION OF CLOUD DURATION.

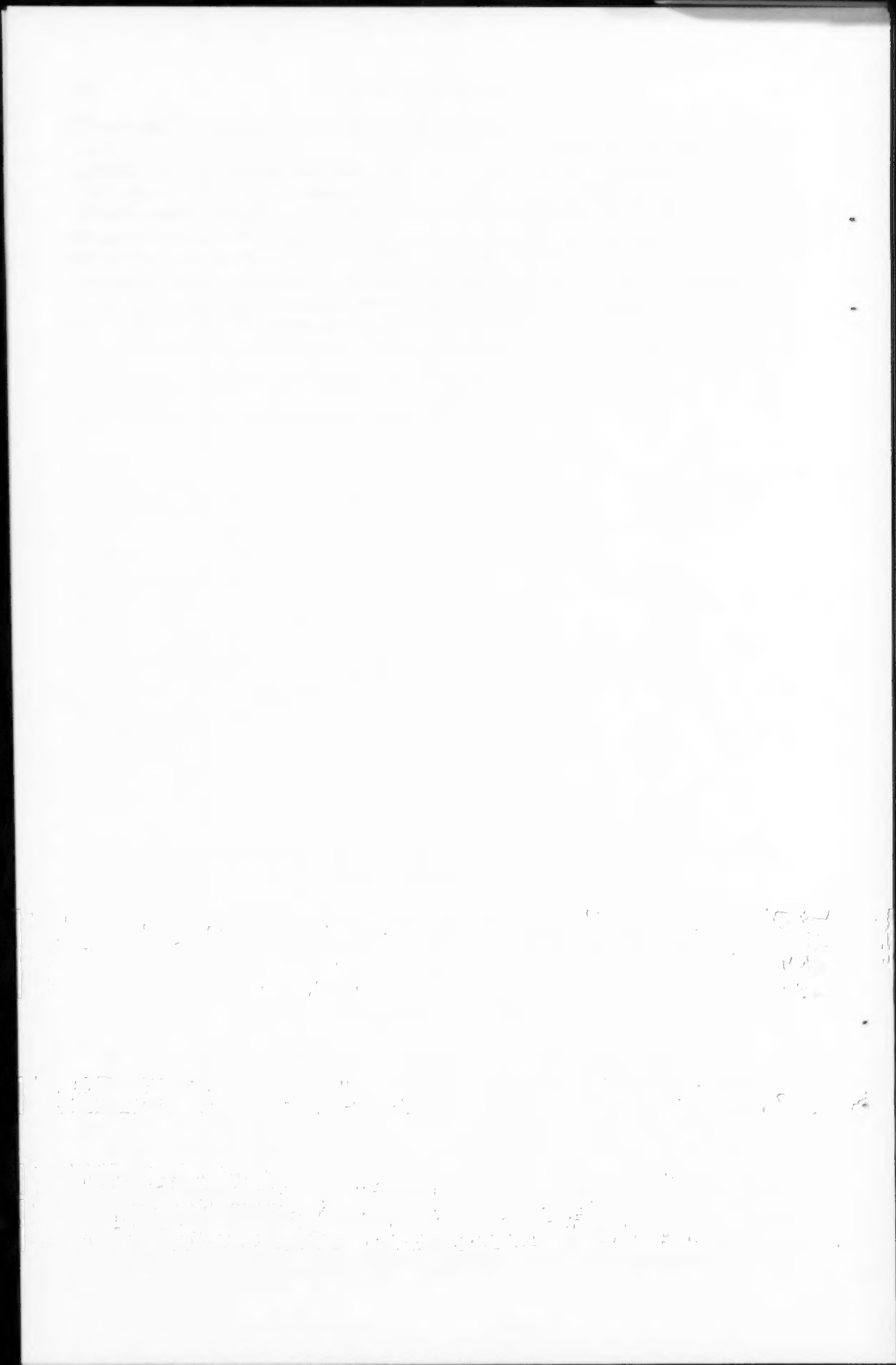
#### FURTHER OUTLOOK

It is a good sign that people engaged in cloud-seeding should be turning more and more to the matter of physical evaluations in assessing seeding experiments. Only in this way can the understanding of the basic processes be extended and only in this way can advances be made in seeding technology.

It is a serious mistake, however, to believe that physical evaluations will provide a quick or easy answer to the problems. The basic requirements for a physical evaluation are no different from those needed for a purely statistical evaluation. In either case, very little evaluation of seeding efficacy is possible unless the original data are taken in accordance with the best principles of experimental design. Basic to this problem is the requirement that the data

be taken in such a way as to provide an adequate "control" group of data against which to judge the outcome of the experiment.

It is also important for scientists and interested lay people alike to realize that we may be looking for a very precious "needle" in a very large "hay stack". We must have patience and we must be willing to support scientifically designed seeding experiments over long periods of time. The latter seems to be difficult in the United States. We must recognize our debt to our Australian friends who have provided one of the very few examples of an adequately designed seeding experiment performed year after year until sufficient data were accumulated to permit a conclusion at a significant level of confidence. We will do well to follow their example.



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Journal of the  
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EVALUATION OF SEEDING TRIALS<sup>a</sup>

By Arnold Court<sup>1</sup>

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SYNOPSIS

Proper evaluation of a cloud-seeding program, from the customer's standpoint, should be in terms of his desired end product: kilowatts, bushels of grain, or pounds of meat. Failing this, and for the benefit of meteorology, evaluation should cover all possible effects of cloud seeding: rain intensity, rain temperature, wind speed, etc. Exact purpose of the program, and methods to be used in its evaluation, must be stated beforehand, and certain statistical pitfalls must be avoided, for the evaluation to be acceptable.

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PROGRESS AT DENVER

In 1952 the Weather Modification Operations Analysis Project of the National Weather Improvement Association, Inc., "an organization of the farm and ranch groups which purchase the services of commercial rainmakers or cloud seeders" met in Denver, Colo. A few of the results of that one-day round-table are worth quoting, to indicate the progress, or lack thereof, in cloud seeding evaluation.

"The most effective method of eliminating bias," the group decided, and thus reducing the chances of variations in result, is agreement before the in-

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August 1959 Weather Modification Conference in Denver, Colo.

<sup>1</sup> Meteorologist, Pacific Southwest Forest and Range Experiment Station, Forest Service, U. S. Dept. of Agric., Berkeley, Calif.

vestigation as to all of the terms and conditions, such as, for example, the manner of selecting controls . . ."

That was a conclusion in 1952, yet in 1959 many weather-modification operations are conducted not only without prior decision as to controls to be used, but even without clear-cut specific statements of intent, to which the results can be compared. Without a prior declaration of purpose, one can claim to have caused—or not caused—any unusual weather event. Since weather always is unusual, such claims can be spectacular.

Sometimes the objective is defined—or redefined—after the operation is over, when rainfall and streamflow data are already at hand. Should the evaluation of a cloud-seeding project to increase mountain snowpack, so that more streamflow will be available for hydroelectric generation, be based on the streamflow of the whole year or only on that of the spring and summer? If one is to pick a period of months of arbitrary length, that is from 1 to 12, and with arbitrary beginning, 144 choices are possible. If the choice is restricted to the half-year beginning in March, to reflect the results of seeding, 21 different selections are possible, ranging from the full half-year March-August to each of the individual months. Although the treatment has no effect whatever, when all of these 21 possible evaluation periods are studied, one of them is likely to show an effect significant at the 5% level.

No matter which of the possible periods is chosen, if it is not designated until the test data are available for inspection, the choice will be subject to attack. The only perfect way of preventing such doubts is to announce publicly, before the operation starts, what is intended, and exactly on what basis it will be evaluated. Two papers, by A. S. Dennis<sup>2</sup> and W. E. Howell,<sup>3</sup> indicated that the method of analysis had been unchanged after the first year of operation. This is quite proper.

#### STORM VS. SEASON

It is agreed that there is a reduction in the earth's rate of rotation each time a satellite is fired, since the angular momentum of the two-body system, earth and satellite, remains fixed. That the rotation rate has been reduced is accepted in principle—but the magnitude of the effect is so slight that watches needn't be retimed after each firing. Similarly, that the introduction of nuclei into a cloud alters the precipitation mechanism is agreed upon—but whether it is sufficient to require redesign of irrigation and drainage works is the question.

"To evaluate" means, according to the dictionary, "to ascertain the value or amount of, to appraise carefully." Methods of evaluation were the major topic of discussion in 1952, just as at present (1959).

"The needs of the group paying for evaluation must to some extent determine the method of analysis used," it was concluded at the round-table. "For example, the operator is concerned with finding the optimum number of generators per unit of ground, in order to minimize his operating costs. For this purpose, analysis of individual storm types may produce the greatest value.

"The farmer who is concerned with the timing of storms, and maximizing precipitation from specific storms at specific times, may be best served by the same type of analysis. The irrigator, stockman, and reservoir owner, how-

<sup>2</sup> "Cloud Seeding Results in Santa Clara County," by A. S. Dennis, Journal of the Irrigation and Drainage Div., Proceedings of the ASCE, Vol. 86, No. IR 1, March, 1960.

<sup>3</sup> "Seeding of Clouds in Tropical Climates," by W. E. Howell, Journal of the Irrigation and Drainage Div., Proceedings of the ASCE, Vol. 86, No. IR 1, March, 1960.

ever, are concerned primarily with seasonal or annual precipitation. This group may desire seasonal analyses . . ."

Unfortunately, however, seasonal analyses are not very powerful, unless a very long and homogeneous historical record is available. Usually the actual operation will provide only one seasonal value, of average precipitation or total streamflow. To determine its significance, an estimate is needed of what would have occurred in the absence of treatment. But such an estimate, based on past conditions and on what happened around the target, rarely is precise enough to detect the sort of treatment effect that is intended.

Statistical precision is enhanced by increasing the sample size, using monthly or storm totals instead of the seasonal total. Use of storm totals, however, is fraught with danger. Storm totals do not correlate as well, between areas, as do totals for months or seasons. In addition, use of storm totals uncovers a methodological pitfall that will be noted subsequently. Furthermore, analyses in terms of storms do not answer the customer's question: he wants to know how much benefit he received in the program as a whole, not storm by storm.

Actually, few purchasers of cloud-seeding services want water itself. Most of them want kilowatts, or bushels of wheat, or pounds of beef, or some other end product. A complete evaluation of a cloud-seeding operation should be in terms of this end product, certainly not in terms of the strength of a radar echo or even the catch of a group of raingages during a storm.

Such economic evaluation, unfortunately, is far more difficult than the customary meteorologic or hydrologic evaluation, and thus has been attempted for very few operations. Nevertheless it should be the eventual goal of cloud-seeding evaluation. The lack of progress in this direction in seven years indicates that much work lies ahead. One form of economic evaluation has been tried in hail-suppression projects, where the market value of the crop under protection provides a measure of the degree of success.

#### UNDESIRABLE EFFECTS

Economic evaluation, in terms of the end product, is necessary because some results of cloud seeding may be more harmful than the primary result; increased precipitation is beneficial if it is achieved. Rainfall amount cannot be increased without affecting either the duration or the intensity, if not both. And increase in either of these aspects of precipitation may be harmful.

For an investigation of rainfall intensity in some California cloud-seeding operations, the first record studied was that of the recording gage at Santa Ynez, in the middle of Santa Barbara county. There the intensity was significantly greater during four winters of seeding, 1951-53 and 1955, than during twelve winters without seeding. Other gages in Santa Clara and Santa Barbara counties seem to show similar relations, but the study has just begun.

Other aspects besides amount-duration-intensity may be altered, to some degree, by any successful treatment to increase the amount. Increase in intensity usually is accomplished by an increase in drop size; the larger drops fall faster and have more thermal mass than small ones, and hence are somewhat colder when they reach the ground. Is this good, or does it make any difference?

Winds accompanying the rain may be affected by the treatment. Just like the surgeon who claimed that the operation was successful even though the patient died, a cloud seeder conceivably could provide enough rain to save a crop—and a strong wind to blow it flat on the ground. Cloud seeding has been

used to prevent damaging winds, but as yet no reports on principles, methods, or success are available from the two seasons of work in Columbia, or from the similar project in Panama.

Meteorologists have been surprisingly unimaginative in outlining the probable results of any successful alteration of natural precipitation mechanisms. R. R. Braham<sup>4</sup> indicated some of the changes in cloud properties that may be caused by artificial nucleation, but did not consider what would be the effects on the ground. No cloud-seeding operation, commercial or experimental, has been truly evaluated or "appraised carefully" by study of all aspects of precipitation. After a dozen years of spasmodic experimentation and commercial exploitation, cloud seeding really should be evaluated from all aspects.

### LIGHTNING AND FIRES

This evaluation is being tried, in a small way, in an experiment being conducted in northeastern California. It is "Project Eagle" of the Division of Forestry, California Department of Natural Resources. The Pacific Southwest Forest and Range Experiment Station of the United States Forest Service is evaluating the study, under contract. The basic purpose of the experiment is to seed cumulus clouds—perhaps overseed is a better term—to prevent them from developing into thunderstorms which would cause lightning that would set the forests ablaze.

But the evaluation involves much more than lightning, and the number of lightning-caused fires. Nine recording raingages have been installed in the 400-sq-mile target area, so that the amount and intensity of rainfall can be studied; as yet neither drop size nor rain temperature is measured (as of 1959). Special lightning counters have been installed; although they may not give true absolute counts, they don't know which days are treated and which are not, as the project is completely randomized. Their readings should be indicative of lightning activity, unless the very character of lightning is altered by cloud seeding.

The evaluation of this cloud seeding trial will involve not simply one, but many items:

1. Amount of precipitation;
2. Intensity of precipitation;
3. Amount of lightning activity;
4. Number of forest fires set by lightning;
5. Number of man-caused fires; and
6. Flammability of forest fuels.

Still more interesting items may be added, but gathering the data to evaluate these six items is sufficient to keep the meteorologists on the project quite busy.

### TWO PITFALLS

In the actual evaluation of a cloud-seeding trial, as to its effects on rainfall amount and intensity, and other aspects, many pitfalls must be avoided if the result is to be valid. Two of these, in particular, have been stressed by Jerzy

<sup>4</sup> "Physical Evaluation of Seeding Effects II. Physical Properties of Clouds," by R. R. Braham, Journal of the Irrigation and Drainage Div., Proceedings of the ASCE, Vol. 86, No. IR 1, March, 1960.

Neyman. They may be called the pitfalls of comparability and of transformation.

The comparability pitfall lies directly in the path of any evaluation of precipitation increase by storm periods. In the usual analysis, a target-control rainfall regression is established using many pre-treatment seasons. Then the results of the treated storms or periods are compared to this regression. If the entire month or season is used for this comparison, the pitfall has been avoided. But if the comparison is based only on those hours or days when the silver iodide was being released, the comparability pitfall has claimed another evaluator.

The difficulty is that the historical regression is based on all precipitation, including that which fell during periods which would be called "non-seedable" by the operator. The proper procedure would be to go through the historical weather maps and decide which storms would not have been seeded had a modern operator been active then, and use only the "seedable" storms for the regression. This, incidentally, is what has been done in connection with the Santa Barbara project.

The transformation pitfall awaits the evaluator who takes the logarithm or the square root, or some other transformation, of the rainfall or streamflow; he builds his regression and makes his comparison in terms of such transformed data, and then wishes to indicate, in the original units of inches or acre-feet, the magnitude of the treatment effect. Transformations are made for one of two reasons, or both. They may be required to obtain a linear relation, or to achieve uniformity of variance about a regression.

Transformations made to linearize a relation may be of any sort, but those made to attain uniformity of variance are all of the same type. For conclusions to be drawn readily, the scatter of points about a regression line (straight or curved) should be more or less uniform all along the line. Often, however, the scatter increases with increasing values of the two variates. This undesirable feature is eliminated by transforming one of both variates. Of necessity, the transformation is convex upward—such as a square root.

If a variate  $y$  is proportional to the square of another variate,  $x$ , which is to be used to predict future values of  $y$ , one can use, not  $x$  and  $y$ , but  $w$  and  $y$ , where  $w$  is  $x^2$ . Alternatively, the regression may be computed in terms of  $x$  and  $z$ , where  $z$  is the square root of  $y$ . A third approach is to take the logarithms of both  $x$  and  $y$ , which also gives a linear relation.

Of these three methods, only the first avoids the transformation pitfall, because it involves transformation of the predictor variable only, and does not affect the dependent or predicted variable,  $y$ . In either of the others, the problem lies in going from the predicted values of the transformed variable ( $z$  or  $\log y$ ) to that of the variable itself ( $y$ ).

The quantity of interest is a conditional expectation; that is, it is the expected value of the dependent variable ( $y$ ) under the condition that the predictor or "independent" variable has a certain value. Such an expectation is an average, and the average of the transforms is not the same as the transform of the average. Because transformations are non-linear (they would be pointless if they were linear), the predicted value of  $y$  cannot be obtained by simply inverting the transformation. For a given value of  $x = x_1$ , the regression declares that the average (or expected or predicted) value of  $z$  is  $z_1$ . But the average value of  $y$  corresponding to the same  $x_1$  is not the square of  $z_1$ . Instead, it is something less, in general, but how much less depends on how different  $x_1$  is from the average value of  $x$ .

Details of this inverse transformation pitfall, and methods of computation to avoid it, are contained in a paper by Neyman and Elizabeth Scott. They feel that in most of the published cloud-seeding evaluations using square root, logarithmic, gamma function, or similar transformations, the estimated increases in precipitation are significantly greater than would be estimated by the proper technique.

### CONCLUSIONS

What then is the present status of cloud-seeding evaluations? Has any progress been shown in the dozen years since the first experiments, or in the years since the 1952 conference in Denver? Certainly methods are improving, and evaluations are becoming more reliable. In fact, the quality of evaluations is increasing much faster than the fault-finding of the statisticians. At the present rate, it will soon meet all these objections—and even those that will be raised in the future.

Eventually evaluation must be in economic terms, so that the customer can ascertain exactly whether he is receiving a fair return for his expense. Such evaluation requires work by economists and others to develop a method of predicting yield (crop, electric, etc.) from all factors, including weather. Until such estimates are possible, meteorologists will continue to evaluate the meteorological effects of cloud-seeding—but they must consider all meteorological effects, not just the one that is desired, and list them all beforehand.

Comparability of all data must be assured, and transformations handled properly. Other difficulties with current evaluations, not cited herein, can also be overcome. Then the efficacy of cloud seeding will finally be subject to rigorous and unassailable evaluation.

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NATURAL VARIABILITY OF STORM, SEASONAL,  
AND ANNUAL PRECIPITATION<sup>a</sup>

By Glenn E. Stout<sup>1</sup>

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SYNOPSIS

Since about 1949, the Illinois State Water Survey has operated four networks of closely spaced recording rain gages on areas up to 500 sq miles. The records readily display the storm, seasonal, and annual variability of mid-western precipitation under natural conditions. Statistical evaluation of seasonal and annual rainfall variability are presented. Analyses were made showing the variability of natural rainfall which may occur between five comparable areas to show the differences that may naturally occur between control and target areas. Another study showed an 18% difference in the average annual precipitation within an urban area. Results are applicable in the design of rain gage networks for the evaluation of weather modification experiments.

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INTRODUCTION

The ultimate aim of most weather-modification operations is to increase the natural precipitation. The end product is then either soil moisture or runoff, which are vital to most any economy. Small increases in precipitation at critical periods to supplement normal precipitation are often very beneficial. Therefore, it is important that research be performed to study the mechanism of precipitation formation.

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<sup>a</sup> Presented at the August, 1959, Weather Modification Conference in Denver, Colo.

<sup>1</sup> Head, Meteorology Section, Illinois State Water Survey, Urbana, Ill.

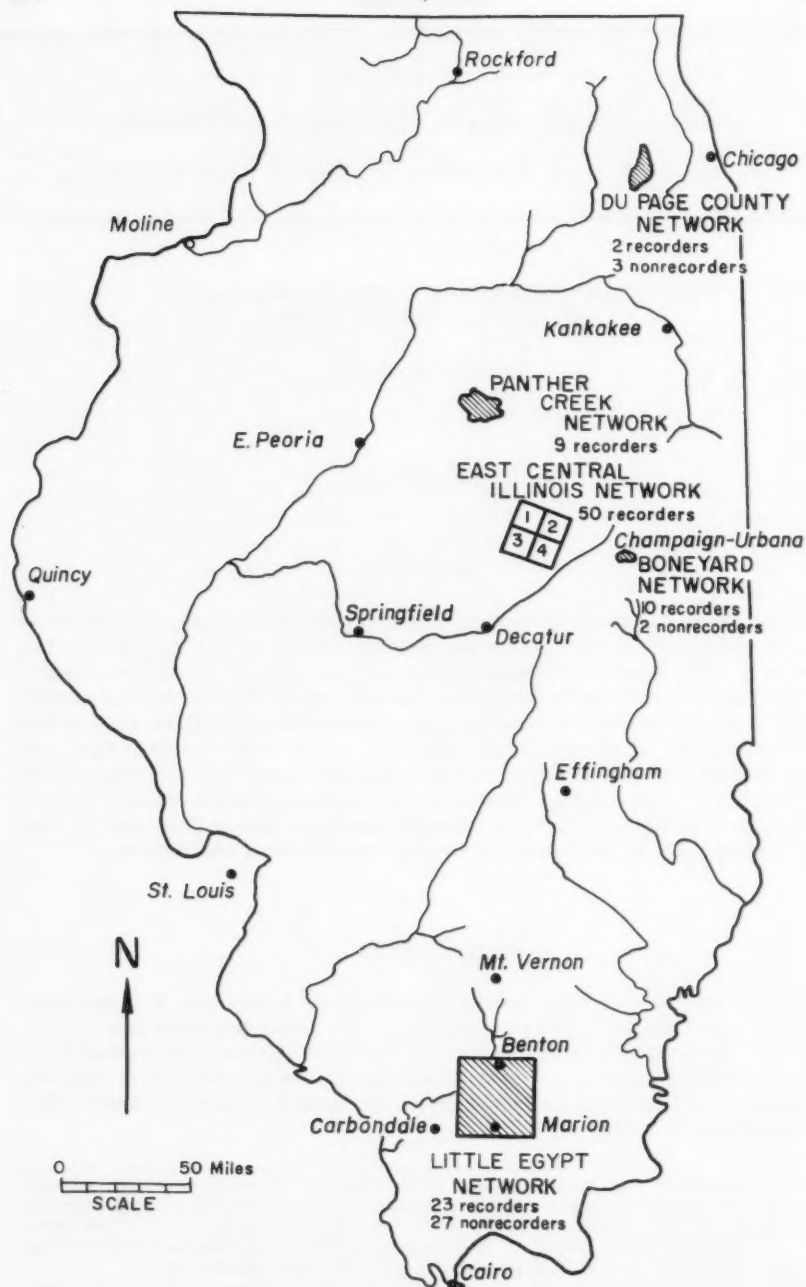


FIG. 1.—DENSE RAIN GAGE NETWORKS IN ILLINOIS.

It is also necessary to study the distribution of the natural precipitation at the surface of the earth in order to determine its areal and temporal variability, to develop methods of measuring precipitation accurately, and to provide data for the engineer or meteorologist to use in the design of precipitation networks. The Illinois State Water Survey has been engaged in studies of this nature since the announcement of the Langmuir-Schaeffer seeding experiments. This paper discusses some of the recent work of the Water Survey and presents data and results applicable in the design and evaluation of weather modification by artificial means.

Great variability in warm-season storm rainfall was readily evident early in the study. After data for several years had been compiled, large differences in monthly and seasonal amounts between stations also became apparent. Since 1956, three of the rain-gage networks have been operated continuously to record the cold season as well as the warm season precipitation. The fourth rain-gage network has been operated continuously since 1949. Analysis of these data has revealed considerable areal variability in cold season and annual precipitation.

Three of the networks are located in central Illinois and the fourth network is located in southern Illinois (Fig. 1). The Boneyard network in the urban

TABLE 1

Network	Elevation (msl) and Location	
	Maximum	Minimum
East Central	790 (NW)	690 (SE)
Panther Creek	750 (E)	710 (W)
Boneyard	780 (W)	715 (E)
Little Egypt	550 (E)	390 (S & W)

area of Champaign-Urbana consists of ten recording and two non-recording rain gages in an area of about 10 sq miles. The East Central Illinois network, located about 25 miles west of Champaign-Urbana, includes fifty recording rain gages arranged in an approximately homogeneous pattern over an area of 400 sq miles. The Panther Creek network is located near El Paso, Ill., about 70 miles northwest of Champaign-Urbana. The network consists of nine recording rain gages in an area of 95 sq miles on the Panther Creek watershed. Centered around West Frankfort, the Little Egypt network in southern Illinois consists of twenty-three recording and twenty-seven non-recording rain gages spaced over an area of 540 sq miles. All of the recording rain gages are serviced weekly by Survey personnel. Extreme care was exercised in installing the equipment in order to insure adequate exposure.

The networks are located in areas of relatively flat land, as indicated in Table 1. Much of the area of the networks is under cultivation, except for the urban area where the Boneyard network is located. None of the gages are located in forested regions.

## STORM, MONTHLY, AND SEASONAL PRECIPITATION

The great variability in storm, monthly, and seasonal precipitation that can occur during the warmer half of the year on the East Central Illinois network is shown in Fig. 2. On May 15, 1958, Fig. 2(a), rainfall varied from 2 in. to less than 0.50 in. within a distance of 3 miles. Most of the rain fell over the southeast corner of the network. In Fig. 2(b), thunderstorm activity caused rain to vary from 1.57 in. to 3.96 in. The maximum rainfall gradient of 0.80 in. per mile was observed on the map in the southeast corner of the network.

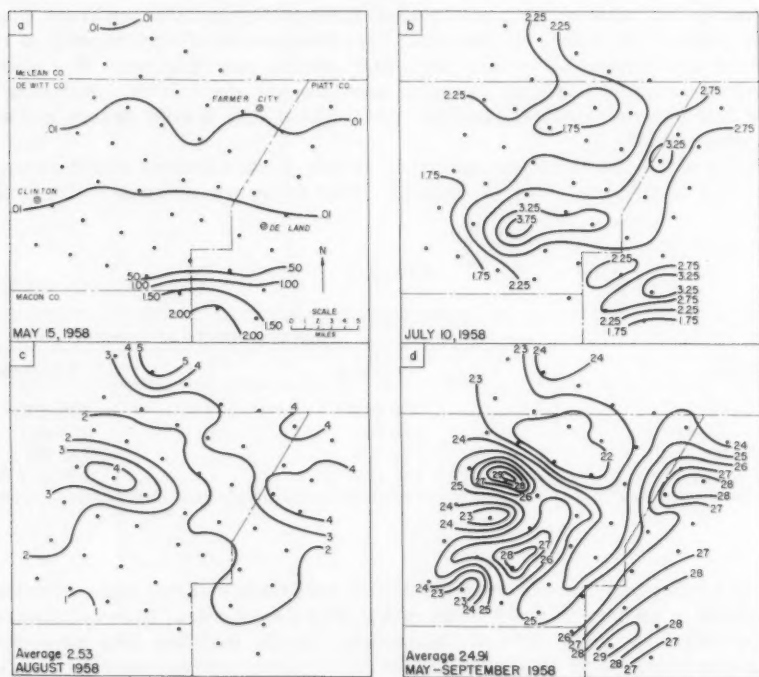


FIG. 2.—STORM, MONTHLY, AND GROWING SEASON RAINFALL PATTERNS.

The average precipitation over the network for August, Fig. 2(c), was 0.70 in. below normal, but monthly amounts varied from 5.50 in. in the northern portion to less than 2 in. near the center, increased—again southward—to 4.78 in., and then decreased to 1.02 in. near the southern boundary. During the 1958 growing season of May through September, amounts varied from 21.16 in. to 29.72 in., Fig. 2(d). The normal rainfall at the Weather Bureau station in Clinton is 19.07 in. The largest amount recorded was 40% greater than the lowest gage report.

Fig. 3 illustrates the variability in precipitation during the winter or cold season on the East Central Illinois network. These isohyetal maps were pre-

pared from the records of twenty-five rainfall stations instead of the fifty normally in operation. The distribution of precipitation during the extremely damaging ice storm of January 20-21, 1959, in central Illinois is shown in Fig. 3(a). Precipitation varied from a low of 0.72 in. to a high of 1.80 in. The melted water content resulting from the heavy, wet snowfall of March 9-10, 1959, is shown in Fig. 3(b). The lowest amount was 0.09 in. while the highest amount was 0.62 in., and the snowfall varied from about 1 in. to over 6 in. The precipitation pattern during February, 1959 is shown in Fig. 3(c). A maximum difference of 1.17 in. in a distance of 8 miles was recorded. The precipitation for November, 1958 through February, 1959 is shown in Fig. 3(d). Seasonal

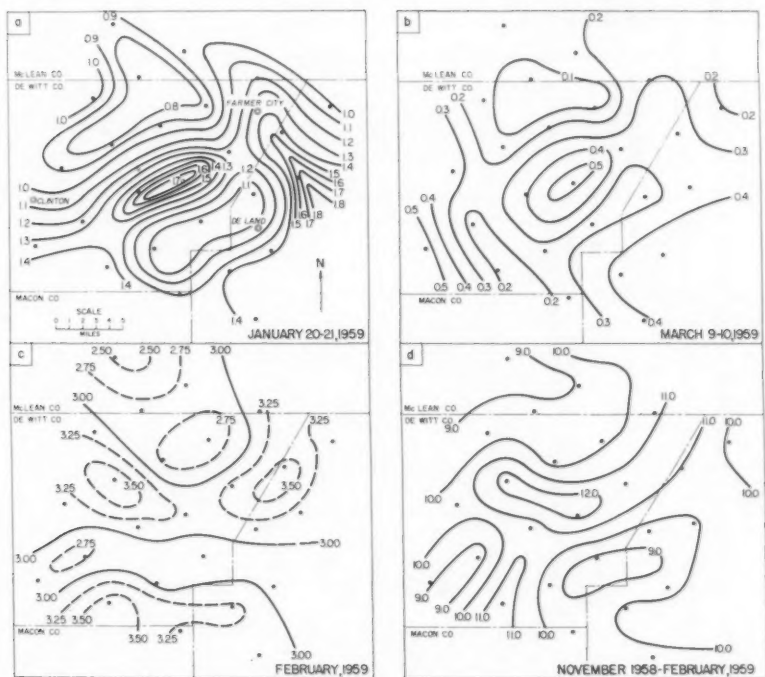


FIG. 3.—STORM, MONTHLY, AND MID-WINTER PRECIPITATION PATTERNS.

values varied considerably with distance. A maximum range from 8.56 in. to 12.23 in., or a seasonal difference of 3.67 in., was recorded in a distance of 9 miles.

#### ANNUAL PRECIPITATION

Since 1956, annual operation of the dense rain-gage networks has provided data on the variability of annual precipitation. Table 2 shows the mean annual precipitation on each network for each year of record, highest, and lowest station amounts, percentage of the mean, difference, and distance between the

March, 1960

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TABLE 2.—ANNUAL RAINFALL STATISTICS FROM DENSE RAIN GAGE NETWORKS

Network	Year	Square Mile per Gage	Mean Rainfall in inches	Highest Amount in inches	% above Mean <sup>a</sup>	Lowest Amount, in inches	% below Mean <sup>a</sup>	Difference in Highest and Lowest Amounts, in inches	Distance Between Highest and Lowest Amounts in miles	Maximum Point-to-Point Difference, in inches per mile
East Central	1958	16.0 <sup>b</sup>	34.20	41.15	20	30.95	10	10.20	5.5	2.26
East Central	1957	14.9 <sup>b</sup>	39.95	46.67	17	33.60	16	13.07	7.5	2.94
Boneyard	1958	1.25	34.41	39.80	16	30.01	13	9.79	3.0	8.28
Boneyard	1957	1.50	39.11	43.52	11	35.01	22	8.51	4.5	7.20
Little Egypt	1958	10.8	45.05	54.38	21	39.40	13	14.98	22.0	3.26
Panther Creek	1958	10.6	29.11	38.06	31	24.05	17	14.01	8.5	4.12
Panther Creek	1957	10.6	35.82	43.26	21	32.83	8	10.43	4.0	4.82
Panther Creek	1956	10.6	19.33	25.19	30	14.92	23	10.27	4.0	2.33
			<sup>a</sup> $\frac{\text{High or Low Value} - \text{Mean}}{\text{Mean}} = \% \text{ of Mean}$		<sup>b</sup> Cold-season distribution of gages.					

highest and lowest amounts, and the maximum point-to-point difference in inches per mile. A maximum difference of 8 in. per mile was observed on the small Boneyard network in 1958, while the three larger networks had maximum differences ranging from 2 to 5 in. per mile during 1956-58.

#### ANNUAL PRECIPITATION VARIABILITY

Fig. 4 shows the annual precipitation pattern for central Illinois in 1958, based on data from three dense networks and on data from the twenty-eight U. S. Weather Bureau (USWB) climatological stations. Considerably greater

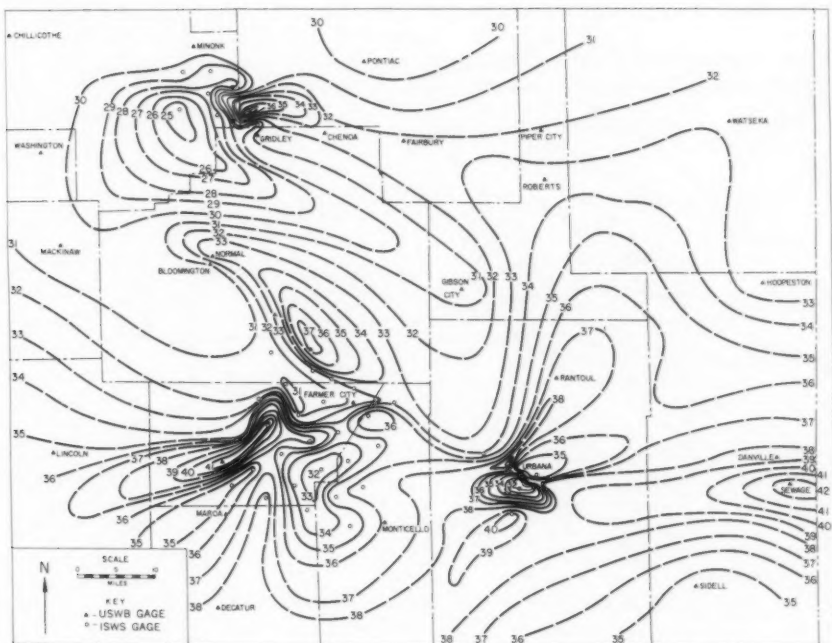


FIG. 4.—1958 PRECIPITATION PATTERN AS BASED UPON WATER SURVEY DENSE NETWORK DATA AND USWB CLIMATOLOGICAL DATA.

detail is evident in the regions of the dense networks. Precipitation ranged from 32 in. to 39 in. in the Champaign-Urbana area, and from 31 in. to 41 in. in the area within the fifty gages in the East Central Illinois network, located west of Champaign-Urbana. In the Panther Creek network, values ranged from 25 in. to 38 in.

The precipitation pattern for 1958, based solely on the data from the Weather Bureau climatological stations, is shown in Fig. 5. The steep gradients of precipitation evident in Fig. 4 are eliminated, although there is still considerable variability present. Long-term climatological records indicate that the average annual precipitation in this region increases from 34 in. in the north to 37 in. in the south.

## ANNUAL SMALL-SCALE VARIABILITY

Variations within short distances, as exhibited in the patterns of precipitation for 1957, might be considered as having a minor effect on the average annual precipitation pattern. However, the 10-yr average distribution of precipitation in the Boneyard network (Fig. 6) indicates otherwise.<sup>2</sup> Average values vary from 30 in. to 35 in. within this network of 10 sq miles. The heavier precipitation in the central part of the Champaign-Urbana area may be due to urban effects. Although the exact cause is not known, the greater amount of precipitation could be attributed to several factors. Increased turbulence from

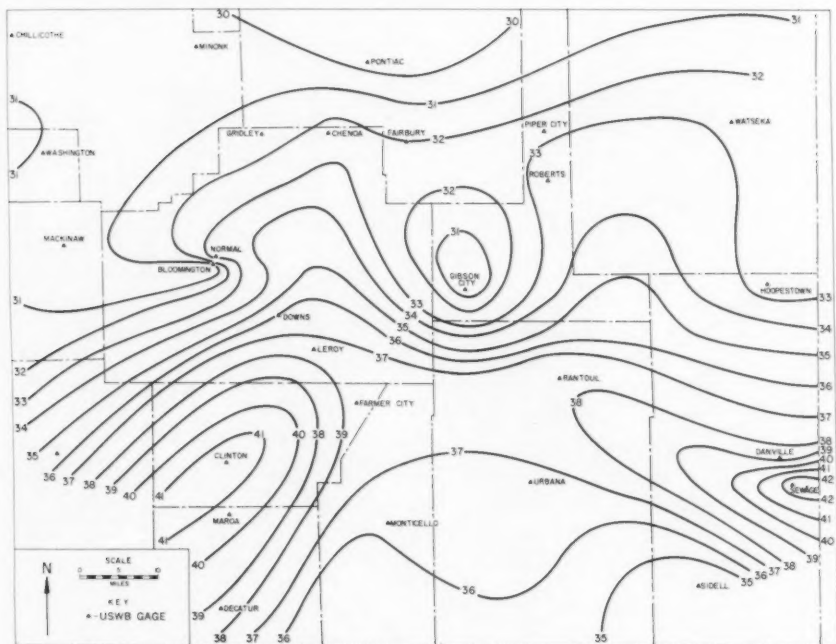


FIG. 5.—1958 PRECIPITATION PATTERN AS BASED ON USWB DATA.

local heating, greater mechanical mixing of the air, and a greater concentration of condensation nuclei in addition to increased water vapor from combustion processes may have been influential in the production of 18% more rainfall over the central section of the urban area. It is also conceivable that a rain gage in an urban area may collect more precipitation due to shielding from the surrounding buildings. That is, the shielding could reduce the wind and limit the turbulence in the vicinity of the gages, so that they collect a larger amount of precipitation than would be possible in an open exposure, where there is no obstruction to the wind field for several miles.

<sup>2</sup> "Summary of Weather Conditions at Champaign-Urbana, Illinois," by S. A. Changnon, unpublished, Illinois State Water Survey, Urbana, Ill., 1959.

H. E. Landsberg compared<sup>3</sup> the precipitation recorded by a gage at a city office with one at an airport for Tulsa, Okla. He found approximately 8% more precipitation at the city office than at the airport station. Other studies or references support these data. He believes that nucleation and turbulence both contribute to the increase but their influence on the precipitation process varies depending upon the different synoptic situations.

Tor Bergeron reports<sup>4</sup> that he finds heavier rainfall in the forested regions of Sweden than in the meadow areas. He has suggested that the increase of moisture from evapotranspiration and frictional effects are factors in producing greater precipitation in wooded areas.

The larger difference found in the Champaign-Urbana study may also be partly due to the denser network since extreme values are easier to observe with greater density of sampling points.

Therefore, when one is looking for small differences in precipitation, care must be exercised in the selection of past data or in the establishment of new observational stations.

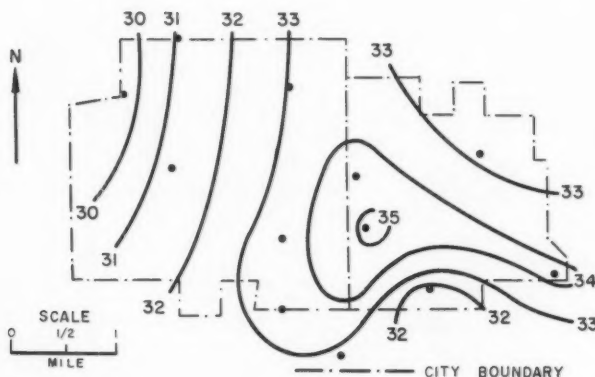


FIG. 6.—AVERAGE ANNUAL PRECIPITATION FOR CHAMPAIGN-URBANA, 1949-1958.

#### CONTROL VERSUS TARGET PRECIPITATION

In order to determine the natural variability in precipitation between target and control areas, the East Central Illinois network was subdivided into four areas of 100 sq miles each. Only data for recent years were used, since the distribution of gages varied somewhat from year to year prior to 1956. Since the distance between the center of the East Central Illinois network and the center of the Panther Creek network was approximately 55 miles, it was decided to use both sets of data. In order to separate the target area from the natural conditions, one might want to separate the two areas by such a distance.

<sup>3</sup> "The Climate of Towns," *Man's Role in Changing the Face of the Earth*, by H. E. Landsberg, University of Chicago Press, Chicago, Illinois, 1956, pp. 584-603.

<sup>4</sup> Lecture on Precipitation, as presented at a Seminar at the University of Illinois by Tor Bergeron, Urbana, Ill., June 16, 1959.

*Warm Season Rainfall.*—Table 3 shows the warm season rainfall, May through September, for each of the 100-sq-mile areas for 3 yr. Numerous comparisons could be made.

For example, Panther Creek network was compared with area No. 1 of the East Central Illinois data, since these areas are approximately 45 miles apart. The maximum difference of 5.59 in. was recorded in 1956. In other years, differences of 3.26 in. and 2.70 in. were recorded.

If only the four subdivided areas of the East Central Illinois network are considered, the maximum range between the areas was 1.25 in. or 8% in 1956, 2.78 in. or 18% in 1957, and 3.56 in. or 16% in 1958. The average range between 100-sq-mile areas in these 3 yr was 7%.

TABLE 3.—MAY THROUGH SEPTEMBER MEAN RAINFALL (INCHES)

Year	Panther Creek	East Central Illinois				
		No. 1	No. 2	No. 3	No. 4	Entire Network
1956	11.35	16.94	15.69	16.13	16.00	16.19
1957	14.32	17.58	18.27	18.23	15.49	17.39
1958	19.94	22.64	25.27	25.39	26.20	24.88

TABLE 4.—WARM SEASON DEPARTURES FROM EAST CENTRAL ILLINOIS NETWORK MEANS

Area	1956		1957		1958	
	Inches	%	Inches	%	Inches	%
No. 1	0.75	5	0.19	1	2.24	9
No. 2	0.50	3	0.88	5	0.39	2
No. 3	0.06	0	0.84	5	0.51	2
No. 4	0.19	1	1.90	11	1.32	5
Panther Creek	4.84	30	3.07	18	4.94	20

The departures in precipitation between the subdivided areas and Panther Creek from the mean precipitation for the entire East Central Illinois network for each area are shown in Table 4. The percentage difference between the 400-sq-mile mean rainfall and the individual areas of 100-sq-mile mean rainfall was found to be as much as 30% during the warm season. Within the 400-sq-mile area of the East Central Illinois network, the maximum difference between a small area as compared with the entire area was 11%.

*Annual Precipitation.*—Table 5 shows the annual precipitation for the five 100-sq-mile areas. The maximum difference between areas was 10.39 in. In comparing Panther Creek rainfall against area No. 1, differences of 3.31 in. and 6.01 in. or 9% and 22%, respectively, are found.

In evaluating the annual precipitation for the four subdivided areas of the East Central Illinois network, it was found that the maximum range between

areas was 5.79 in. or 16% in 1957 and 4.38 in. or 13% in 1958. The average range among the 100-sq-mile areas in these 2 yr was 8%.

The departures from the mean annual precipitation for the East Central Illinois network for each area are shown in Table 6. The percentage differences are approximately the same as that during the warm season.

Therefore, it is apparent that substantial differences can occur in the seasonal and annual precipitation over a 100-sq-mile area under natural conditions. In the design and evaluation of weather-modification experiments in the mid-west, the natural variability in precipitation must be investigated before changes induced by the experimenter can be evaluated.

TABLE 5.—ANNUAL RAINFALL, IN INCHES

Year	East Central Illinois					Entire Network
	Panther Creek	No. 1	No. 2	No. 3	No. 4	
1957	35.17	38.48	40.42	42.19	36.40	39.37
1958	27.69	33.70	35.87	38.08	36.25	35.98

TABLE 6.—ANNUAL DEPARTURE FROM EAST CENTRAL ILLINOIS NETWORK MEANS

Area	1957		1958	
	Inches	%	Inches	%
No. 1	0.89	2	2.28	6
No. 2	1.05	3	0.11	0
No. 3	2.82	7	2.10	5
No. 4	2.97	8	0.27	1
Panther Creek	4.20	11	8.29	23

#### RAINFALL RELATIONS ON SMALL AREAS

F. A. Huff and J. C. Neill have studied<sup>5</sup> in detail the rainfall relations on small areas in Illinois, utilizing the data from the Water Survey networks between 1948 and 1955. Their report presents the results of studies on: the relative variability of storm and monthly rainfall over small areas; the distribution of point and areal mean rainfall rates in shower-type precipitation; area-depth relations on small watersheds; the variation of point rainfall with distance; the areal representativeness of point rainfall in measuring areal mean rainfall on a storm; weekly, and monthly basis; the combined effect of storm size, area, and number of rain gages on the accuracy of storm mean rainfall estimates; relations during periods of excessive rainfall over a 100-sq-mile basin; the relation between point and areal mean rainfall frequencies; and micro-meteorological variations in storm rainfall. Their results are applicable to

<sup>5</sup> "Rainfall Relations on Small Areas in Illinois," by F. A. Huff and J. C. Neill, Bull. 44, Illinois State Water Survey, Urbana, Ill. 1957.

the midwest and other areas having similar climate, precipitation forming processes, and topography. It would be impossible to summarize the results of these studies for this paper. The reader is referred to the original document for details and for the application of these data to engineering and meteorological problems. Several of the studies are applicable in the design and evaluation of precipitation modification programs.

### CONCLUSIONS

Dense networks of gages with similar exposure conditions are needed to obtain reliable precipitation measurements due to relatively large variability in time and space. At times, the natural variability of rainfall between networks of gages in the same region is large enough so that results of efforts to increase precipitation could be either masked or falsely magnified.

Based on limited data, the maximum difference in rainfall during the warm season between a hypothetical target and control areas was found to be as high as 30%. The average difference was 7%. On an annual basis, the maximum difference in rainfall between a hypothetical target and control areas was 23% and the average difference was 8%.

The maximum recorded differences in annual precipitation observed in the several networks varied between 8.5 in. to 14 in. The maximum point-to-point difference in these networks ranged from 2.25 to 8 in. per mile.

A study of 10 yr of precipitation records from recording gages located throughout Champaign-Urbana indicates that the average annual precipitation over the central part of these cities is 5 in. greater than the precipitation recorded on the western edge of the community. Urban effects on the rainfall process are considered responsible for part of this difference.

### ACKNOWLEDGMENTS

Credit is due numerous members of the Meteorology Section who have collected and compiled the mass of data that has been used. Special recognition is due William C. Ackermann, Chief, for his helpful suggestions and guidance and to Floyd A. Huff for his review of the manuscript.

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Journal of the  
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A WEATHER MODIFICATION PROGRAM FOR THE FUTURE<sup>a</sup>

By Howard T. Orville<sup>1</sup>

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SYNOPSIS

The present status of weather modification is described and improvements in present methods are suggested. Recommendations for research which would implement those of the Advisory Committee on Weather Control are included.

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INTRODUCTION

Since about 1947, experiments in weather modification have been conducted throughout the United States, Canada, Mexico, and more than forty other nations throughout the world. These experiments have been designed to dissipate clouds, increase precipitation, inhibit hail or lightning and to disperse fog from airports. Most of the experiments follow the techniques originated and developed by Vincent J. Schaefer,<sup>2</sup> Irving Langmuir,<sup>3</sup> and Bernard Vonnegut.<sup>4</sup>

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March 1960.

<sup>a</sup> Presented at the August, 1959, Weather Modification Conference in Denver, Colo.

<sup>1</sup> Vice Pres., Beckman & Whitley, Inc., San Carlo, Calif.

<sup>2</sup> "The Production of Ice Crystals in a Cloud of Supercooled Water Droplets," by Vincent J. Schaefer, *Science*, 104, Nov. 1946, pp. 457-459.

<sup>3</sup> Final Report Project CIRRUS, by Irving Langmuir, May, 1953.

<sup>4</sup> "Experiments with Silver Iodide Smokes in the Natural Atmosphere," by Bernard Vonnegut, *American Meteorological Society, Bulletin*, 31(5), May 1950, pp. 151-157, 10 figs., 9 refs.

Tor Bergeron<sup>5</sup> laid the ground work for present-day experiments in weather modification by the theory which he propounded in 1933, that rain in appreciable amounts can only be released by ice crystals formed in or transported through sub-cooled water clouds. Several years later W. Findeisen<sup>6</sup> added proof to the Bergeron theory by showing that the coexistence of ice-crystals and sub-cooled water droplets in the right quantities is a necessary condition for the precipitation process to start, and he emphasized the important role of sublimation.

Schaefer<sup>2</sup> and Langmuir<sup>3</sup> demonstrated the role of ice-crystals in the precipitation processes when in November, 1946, Schaefer dropped carbon dioxide (dry ice) into a super-cooled cloud over western Massachusetts. Soon after this historic flight Vonnegut<sup>4</sup> discovered that silver iodide crystals are more effective than natural nuclei and can be dispersed from ground generators—an important economic feature.

Other nucleating agents such as cupric sulphide, kaolinite (a type of clay), water, and, quite recently, carbon black, have been used for weather-modification experiments.

The purpose of this paper is to outline briefly the present (1959) status of weather modification, to suggest improvements in present methods, and then to suggest a future research program which would implement the recommendations of the Advisory Committee on Weather Control.

*Public Law 85-510.*—In July, 1958 Congress passed Senate Bill S-86, and President Eisenhower signed it into law. Public Law 85-510 transfers the activities of the Advisory Committee to the National Science Foundation. A Program of Atmospheric Sciences was set up under the direction of Earl G. Droessler. Grants totalling \$1,380,000 were made in March, 1959, and the National Science Foundation budget for fiscal year 1960 requests funds in the amount of \$2,000,000 for weather modification experiments. It is to be hoped that the National Science Foundation will continue to expand its program to at least \$10,000,000 in the next few years.

*Current Research Effort.*—There are perhaps a dozen cloud-seeding projects of special interest. Some of them are:

1. The Santa Barbara Project. This is a well-designed project first proposed by the Advisory Committee on Weather Control.
2. "Project Skyfire"—continuation of experiments to inhibit lightning in the western forests.
3. Institute of Atmospheric Physics, University of Arizona.<sup>7</sup> A summer time orographic cumulus seeding project with some very interesting results. The use of radar, photography and a special network of rain gauges provides for excellent controls to verify the results.
4. Laboratory and flight research into cloud-seeding effects by the University of Chicago.

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<sup>5</sup> "Physik der Wolken," by W. Peppeler, W. Findeisen and Tor Bergeron, (Cloud physics), Berlin, 1937, 25 p. outline of proposed book.

<sup>6</sup> "Selected Papers on the Physics of Condensation and Precipitation," by W. Findeisen, 3 papers translated from the original German, by A. R. Stickley, 1939, 20 p.

<sup>7</sup> Proceedings of the Seventh Weather Radar Conference, by Louis J. Battan, Miami, Fla. Nov., 1958.

5. Research into the role of atmospheric electricity in the precipitation processes by Vonnegut and Moore<sup>8</sup> and Paul B. MacCready,<sup>9</sup> two separate projects.

6. Weather Bureau Hurricane Project. One phase of this project is to seed hurricanes. R. R. Braham, Jr.<sup>10</sup> has reported on this phase. This is the only project that may eventually involve large-scale massive seeding.

7. Commercial hail-suppression experiments in West Virginia, Nebraska, Colorado, Canada, and California.

8. Carbon black experiments by the United States Navy.<sup>11</sup> These experiments are being conducted in the Bahamas and Puerto Rico with satisfactory results.

9. Continuation of experiments to evaluate Bowen's meteoric dust theory.

10. Army Signal Corps project to dissipate sub-cooled stratus clouds.

11. In foreign countries—Australia, Switzerland, France, Italy—increase precipitation or hail-suppression projects.

The foregoing projects may seem quite comprehensive, but actually the total effort is diminished, when one considers the great importance of the economic and military implications of weather modification. In dollar value the total effort is probably less than two million dollars.

#### RECOMMENDATIONS OF THE ADVISORY COMMITTEE

The Advisory Committee on Weather Control recommended that encouragement be given for the widest possible competent research in meteorology and related fields, that would lead to an understanding of atmospheric processes. The Committee recommended a broad research program that included:

1. The effect of solar disturbances on weather.
2. The factors which control global circulation and those which govern the genesis and movement of large scale storms.
3. The processes which govern the formation of rain and snow.
4. The electrification process in clouds and its role in precipitation processes.
5. The natural sources of condensation and ice-forming nuclei and their role.

A casual review of this program will show that the present research effort has scarcely scratched the surface. Many new projects must be set up under government sponsorship. Adequate support is essential for continuity and stability for long-term projects. And long-term means 10 yr to 15 yr of continuous research by dedicated scientific teams made up of meteorologists, physicists, chemists, mathematicians, and other related scientists.

<sup>8</sup> "Observation of Thunderstorms in New Mexico," by Vonnegut, Bernard, and Moore, 15, June, 1959. Rpt. to Naval Research, Aeronautics and National Science Foundation.

<sup>9</sup> "Lightning Mechanism and Its Relation to Natural and Artificial Freezing Nuclei," by Paul B. MacCready, Wentworth Conference, May, 1959.

<sup>10</sup> "An Exploratory Experiment in Hurricane Seeding," by R. R. Braham, Jr., D6-1 to D6-8, Technical Conference on Hurricanes, American Meteorological Society, Miami Beach, Fla. Nov., 19-22, 1958.

<sup>11</sup> "Preliminary Experiments Using Carbon Black for Cloud Modification and Formation," by F. W. Van Straten, R. E. Ruskin, J. E. Dinger and H. J. Mastenbrook, NRL Report #5235, US Naval Research Laboratory, Oct., 28, 1958.

Talented men with specific projects should be selected and should be allowed freedom of action and wide latitude in choosing methods and goals. Once these teams are formed every encouragement should be given to continuity and security until the goals are accomplished. Nothing is more disheartening or frustrating than to have to stop a program because of lack of funds. Once the original team has to abandon its efforts it is extremely difficult to organize it again. It is costly in funds and time.

#### FUTURE RESEARCH PROGRAM

With the foregoing guiding principles in mind, several projects are suggested as part of a research program for the future.

*Improve Present Techniques and Equipment.*—Present equipment used in weather-modification experiments could be greatly improved. Equipment for dispersing silver-iodide needs to be standardized and calibrated. Present methods of checking generator output are very crude. New and improved types of generators are urgently needed.

Nuclei counters of modern design are required to get background nuclei count as well as frequent air samples after seeding. A new type of counter developed by Eugene Bollay looks very encouraging and holds promise of becoming standard observational equipment.

New types of dispensers for dispersing cupric sulphide, microscopic salt particles, carbon black, and other agents used in seeding experiments are urgently required.

More efficient generators of an entirely new design for use in aircraft, large balloons, rockets, and guided missiles should be developed at the earliest possible date.

New and more effective methods should be developed to permit tracking the silver-iodide smoke from ground generator to the target cloud. Routine checks of plume and concentration of nuclei should be made possible by the development of new instruments which are not even on the plotting board at this time.

Improvement in instrumentation and equipment might well improve the efficiency of present cloud seeding techniques by 100% at least and possibly as much as 1,000%. This is the writer's personal estimate of how crude some of the present experimental equipment is. Without meaningful and accurate data we are only working in the dark. Regardless of whether small scale or large scale cloud-seeding experiments are being conducted, the lack of reliable observational data only adds confusion and uncertainty to the findings being reported, needlessly prolonging the day when we can know or understand (a) atmospheric processes; (b) what happens when we seed a cloud; (c) why one experiment fails and another succeeds; (d) when to seed and when not to seed; and (e) when the full capabilities and limitations of present weather modification techniques can be determined.

*Large Scale Seeding Experiments.*—The modification of large-scale weather patterns is of such great economic and military potential that active research should be started at the earliest practicable date. R. D. Elliott<sup>12</sup> has suggested that Langmuir's periodic seeding experiments in New Mexico in 1951<sup>13</sup> be

<sup>12</sup> Preliminary Statement on Drought Suppression, (manuscript), Proposal submitted to Advisory Committee on Weather Control by R. D. Elliott, July, 1954.

<sup>13</sup> "A Critique of the Design of Experiments on Cloud Seeding and Statistical Methods for their evaluation," by Irving Langmuir, General Electric Research Laboratory, Schenectady, Rpt. #55-RL-1263, July, 1955, p. 125-168.

repeated. Others, including Elliott, have suggested that intensive seeding of cyclogenetic areas and frontal zones of long wave (Rossby wave) patterns in the westerlies be initiated. J. Namais<sup>14</sup> has suggested that these "weak" spots, if seeded, might produce large scale effects in the major circulation patterns.

Our meager knowledge of atmospheric processes suggests that any research on large-scale weather patterns be started on a very modest scale, be planned for periods of 5 yr to 10 yr and be expanded only after we have gained experience. Eventually the experimental area might cover a large portion of the Northern Hemisphere. H. Wexler<sup>15</sup> has pointed out the dangers of uncontrolled large scale experiments. He has offered a feasible plan for melting the arctic ice with "clean" atomic bombs, but he has offered the warning that the results might be disastrous.

*Continue Exploratory Experiments on Hurricanes.*—Braham who is participating in the Weather Bureau Hurricane Project has recently reported<sup>10</sup> that during the 1958 hurricane season, exploratory seeding experiments were attempted on four hurricanes. Seeding was actually carried out on one of the storms. While no immediate consequences of the seeding were found, the report gives much valuable information on the scope of the problem and how thoroughly the seeding aspects of hurricanes are being studied.

It is hoped that the Weather Bureau Hurricane Research Program will be expanded and that it is continued for 10 yr to 15 yr if necessary until we learn how to divert them from tracks approaching populous areas or dissipate them at sea.

*Weather Modification Experiments in the Western Mountain Region.*—Based on the findings of the Advisory Committee on Weather Control, there is strong justification for conducting cloud-seeding experiments in all states having high mountain ranges. Several members of the Committee and other meteorologists experienced in weather modification hold the opinion that seeding to increase snowpack would be as successful as in Washington, Oregon, and California (10% to 15% average increase). Such a long range project should cover several states, should be Government-sponsored, and should be supported and coordinated by the National Science Foundation. This program could best be carried out by universities, industries and other institutions having qualified scientific personnel and facilities.

Guidance for such a program could be found in the reports of the Santa Barbara Project, the Institute of Atmospheric Physics at the University of Arizona and the University of Chicago.

*Projects in The Prairie States.*—Possible alleviation of future drought conditions might be feasible if carefully designed and controlled experiments similar to those cited previously were to be established in Texas, the Dakotas, Nebraska, Iowa, Kansas, and Oklahoma. Aircraft, balloons, or weather rockets should be used extensively in these projects to supplement ground generators.

A carefully planned comprehensive proposal for seeding experiments in this area should be developed by one or more teams.

*Subtropical Research in Florida and the Gulf Region.*—An expanded "Project SEABREEZE" should be established along the Gulf of Mexico and the east coast of Florida. Project SEABREEZE<sup>16</sup> was established by the Advisory Com-

<sup>14</sup> "Synoptic and Planetary-Scale Phenomena Leading to the Formation and Recurrence of Precipitation," by J. Namais, Woods Hole Conference, June, 1959.

<sup>15</sup> "Modifying Weather on a Large Scale," by H. Wexler, Science Vol. 128, Oct., 31, 1958.

<sup>16</sup> Final Report of the Advisory Committee On Weather Control, Vols. I and II, Dec., 1957, Government Printing Office.

mittee to study coalescence precipitation processes and the effect of silver-iodide in augmenting rainfall along the Florida coast. More research of this type is needed to gain a better understanding of the coalescence process in initiating precipitation. This should be a continuous project extending over several years and not seasonal as conducted by the Advisory Committee.

### RESEARCH TOOLS FOR THE FUTURE

On the horizon and destined to play an important part in future research projects in weather modification, are earth satellites, high-level balloons, ground and airborne radar, television, weather rockets, high-speed research cameras, and guided weather missiles.

The role of each of these new tools is uncertain at this time (1959), and will have to be determined as the practical applications are developed during the next few years. Earth satellites in combination with radar, television, and other new equipment will be able to keep a constant surveillance of cloud cover, associated storms, and other meteorological phenomena for long periods of time. When this information is coordinated with special surface radar and television networks, as well as reports received from supersonic reconnaissance aircraft and constant-level balloons, we will have developed an observational network which will permit a detailed examination of all weather phenomena. This, in turn, will permit continuous observations of the effect of cloud-seeding or other artificial means for modifying the weather.

Such research tools will be expensive. In order that they may be used to full advantage the national budget for weather modification experiments will most certainly reach an annual figure of at least \$20,000,000.

It is not the purpose of this paper to suggest the detailed uses of the above-cited research tools for the future, but it is believed that any one can readily think of a number of uses that may be made of them in any one of the six projects listed previously. They are all tools for the research program of the future.

### SUMMARY

A weather-modification research program such as the one outlined previously should:

- a. Improve present techniques in cloud-seeding.
- b. Increase our understanding of the precipitation processes.
- c. Substantially increase the snow pack in the western mountain regions.
- d. Provide additional water to the Prairie States and eventually alleviate drought conditions.
- e. Establish criteria to tell when to seed and when not to seed.
- f. Prevent or reduce hazards of hail and lightning and tornadoes.
- g. Develop methods for suppression or diversion of destructive hurricanes.

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THE SANTA BARBARA PROJECT<sup>a</sup>

By Robin R. Reynolds,<sup>1</sup> M. ASCE

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SYNOPSIS

The state of California has set up a gigantic project called the California Water Plan, designed to guarantee adequate water for all uses for many years to come. To determine possible effects of weather modification on this plan, a large experiment was set up involving carefully controlled cloud seeding and evaluation of results. Three years of data are now available but additional data will be needed for conclusive results.

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INTRODUCTION

One of the major accomplishments of the 1959 California legislative session was approval of a giant water-development program. Governor Edmund G. Brown signed the act which will submit the program to the voters for their approval in November, 1960. Upon approval by the voters, water-project construction in California for many years ahead will be assured by \$1,750,000,000 in bonds and by a large portion of the State's recurring tideland-oil revenue.

This action by the Legislature is the culmination of almost 15 yr of study and investigation and the expenditure of funds which probably would aggregate about \$10,000,000. The comprehensive construction program includes many features and projects, one of the most notable of which is an aqueduct, the largest ever constructed, to pump and convey water supplies from the Sacra-

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Note.—Discussion open until August 1, 1960. Separate Discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 1, March, 1960.

<sup>a</sup> Presented at the August, 1959, Weather Modification Conference in Denver, Colo.

<sup>1</sup> Prin. Hydr. Engr., Dept. of Water Resources, Calif.

mento-San Joaquin Delta in the northern part of the state to the vast agricultural, urban and metropolitan areas as far south as San Diego.

During the many years of formulation of this great engineering plan, every aspect of California's water supply and present and future water requirements was studied. One important phase of the coordinated investigation provided an affirmative answer to the question, "Does the State have water supplies which can be developed in an amount adequate to meet the estimated ultimate water requirement?" Another phase of the investigation resulted in the selection of physical works, from among almost innumerable possibilities, which could be constructed to furnish water to meet the State's ultimate water requirements. This engineering plan, which also was adopted by the recent legislature, is called The California Water Plan. Approval by the voters in November, 1960, will provide the financing to construct the major components which are the framework of this plan and upon which other future water projects can be progressively constructed.

In the early phases of the statewide investigation, consideration and study was given to all presently and potentially available water resources including surface water, its natural and artificial regulation; ground water, used both as a separate resource and in coordination with surface water supplies; the conversion of saline and brackish waters; and possible increases in water supply which might result from weather modification operations.

#### STUDIES OF WEATHER MODIFICATION IN CALIFORNIA

It was, of course, coincidental that the early discoveries and experiments in weather modification took place at the same time as the investigation of California's water resources. This coincidence, however, focused attention on weather modification and enabled studies of these techniques to be included in the investigation.

In early 1950, the State Water Resources Board requested that the department's legal staff make a study of "liabilities involved in the creation of artificial rainfall, and powers of the State to regulate the same." This report was prepared and presented to the Board in August, 1950.

The following year, 1951, the California legislature authorized and provided funds for investigation of "... the control of rainfall by artificial means." The results of the investigation were published in State Water Resources Board Bulletin No. 16, "Weather Modification Operations in California," June, 1955.

There were two primary phases to this early investigation. One of the phases consisted of assembling the complete records of all weather-modification operations that had been conducted in California. A continuing program has kept these records up to date. As the second phase of the investigation, all obtainable reports of evaluations of weather-modification operations were reviewed and the methods of evaluation were studied. In addition, an independent evaluation was made of several weather-modification operations. To obtain competent assistance in the field of statistical analysis, the services of the statistical laboratory of the University of California were secured and the major part of the evaluation program was carried out by the laboratory.

Three particular projects were selected for study from the many projects in California. Several years were spent by the laboratory in carefully analyzing precipitation records obtained in these three areas. The results of the analysis indicated that there was no reasonable doubt that the amounts of pre-

precipitation from seeded storms were different from those expected on the basis of unseeded storms. In most instances, but not in all, the differences were increases.

On the basis of such analysis, it appeared strongly probable that weather in California had been modified by cloud-seeding operations. However, it was not possible to state without qualification that the cloud-seeding operations produced the differences. There was the possibility that the storms, which were divided at the suggestion of the laboratory, into classes for the analysis, could be further divided with some of the subclasses favoring the target areas and others the control areas. Undetected changes could have taken place, in the frequency of storms of such subclasses, between the unseeded period and the seeded period. Such changes could have resulted in a natural favoring of the target areas during the seeded period. Based on such objections, which would always be valid when historical data were used, the statistical laboratory was forced to conclude that none of the evidence produced in the investigation, or in any of the other evaluations, constituted documentary evidence of the effectiveness of cloud-seeding.

The statistical laboratory suggested, and Bulletin No. 16 recommended, a procedure for solving the foregoing difficulty and providing documentary evidence of the effects of cloud-seeding. This procedure would consist of prearranging a schedule of cloud-seeding operations under which roughly half of the seeding opportunities would be accepted and seeded while the others would be left unseeded in accordance with the dictates of chance. Such a procedure conducted over a suitable period would provide a sizeable number of storms, some of which would be seeded and some unseeded, for which the amounts of precipitation would be compared and subjected to statistical tests. These tests would be able to measure the probability that seeding was effective. Such a procedure would make it unnecessary to compare present seeded storms with historical data, the relationships for which, as was pointed out, may change.

As a result of the Laboratory's evaluation and of the widespread and continued interest in evaluation of weather-modification operations, the National Science Foundation indicated in 1955, that it would consider donating about \$15,000 per yr for 3 yr to the statistical laboratory of the University of California to evaluate a randomized weather-modification project along the method outlined in Bulletin No. 16, if such a project could be arranged. Independent of this, the supervisors of Santa Barbara County proposed to continue the county's cloud-seeding program. Upon inquiry, they stated their willingness to continue the project on a randomized basis, which would be appropriate for evaluation along the lines outlined in Bulletin No. 16.

In order to complete arrangements whereby the county would conduct the project and the statistical laboratory would evaluate the project, it was necessary that some third agency collect the basic data. Consequently, the Department of Water Resources undertook this responsibility. In January, 1957, the cooperative project was initiated in Santa Barbara County, California, for the purpose of testing the effectiveness of weather modification operations.

#### OPERATION OF THE SANTA BARBARA PROJECT

The primary objective of the Santa Barbara Project is to conduct weather-modification operations by methods that have been aimed, for the past several years, at increasing precipitation in that area. However, a modified schedule, designed to provide a maximum of statistical information will be employed.

This primary objective is achieved by scheduling the actual seeding operation on a randomized basis.

The Santa Barbara Project is unique in that it is a research program specifically designed, with the necessary scientific control and instrumentation, to test the efficiency of the widely used method of cloud-seeding to increase precipitation by using ground-based silver iodide smoke generators.

Earlier research programs in this field, sponsored by the federal government, were usually concerned with special phases of cloud-seeding by techniques intend to produce particular effects. On the other hand, cloud-seeding programs sponsored privately or by local government agencies invariably have been designed to produce maximum additional precipitation, without the expensive instrumentation and reduction in seeding opportunity which is inherent in a program designed for maximum information.

No single agency sponsors the Santa Barbara Project. The project is a cooperative one, undertaken among several major cooperators, with a number of other agencies furnishing consulting advice and occasional assistance. The major cooperators are Santa Barbara County, Ventura County, which joined the project in the third year, the National Science Foundation, the statistical laboratory of the University of California, the California Department of Water Resources, the United States Weather Bureau and the United States Forest Service. In addition, the National Science Foundation and the Department of Water Resources support the activities of another major participant, a private meteorological and research firm with headquarters in Pasadena, Calif. The counties of Santa Barbara and Ventura support the work of another major cooperator, which undertakes the actual cloud-seeding. The Office of Naval Research provided funds to the statistical laboratory to aid in the early stages of the project. Technical advice has also been furnished to the project by the Munitalp Foundation and the Institute of Atmospheric Physics, of the University of Arizona. The President's Advisory Committee on Weather Control has also been of great assistance.

Direction of the Santa Barbara Project is by a Board of Directors composed of representatives of the various organizations involved in the project. This board meets at frequent intervals to review the over-all progress of the project and to assign responsibilities to each of the cooperators.

As noted, the actual cloud-seeding is conducted by a commercial meteorological firm, financed by the counties of Santa Barbara and Ventura. All decisions regarding the seedability of a given storm situation are made by the company that is doing the seeding, based on their analysis of the synoptic situation. On a regular schedule, they contact the statistical laboratory of the University of California at Berkeley by teletype and transmit their decision concerning whether or not a seeding opportunity exists. If a favorable opportunity exists, the final decision of whether or not to seed is made by the statistical laboratory on a random basis. The statistical laboratory is responsible for the evaluation of the results of the operations. The National Science Foundation supports the activities of the statistical laboratory, in accordance with the terms of the Foundation's grant to the Laboratory. The evaluation of the success of seeding is based solely upon precipitation recorded during those units of observation which had been officially diagnosed as seeding opportunities.

The California Department of Water Resources installs and maintains precipitation recording instruments in the target and control areas, and the Department collects, processes, and tabulates the data from these instruments.

The Department also collects and tabulates similar data from instruments of other agencies, in or adjacent to the target and control areas. The department then transmits the tabulated data for all gages to the statistical laboratory for checking and evaluation. The United States Weather Bureau has furnished, on loan to the department, a number of automatic precipitation-recording gages and provides charts for the instruments. These gages will be returned to the United States Weather Bureau at the conclusion of the project.

In addition to the instrument network for collection of precipitation data, an APS-15A radar is operated on La Cumbre Peak, about 6 miles north of Santa Barbara. Lapse-time photographs of the radar screen are taken during storm periods. The camera's field of view also includes meters indicating wind velocity and precipitation rate. Raindrop samples and freezing nuclei observations are obtained at intervals on La Cumbre Peak, and the atmospheric potential gradient is measured continuously.

These data, together with that obtained from other adjacent observing stations and from sondes, are being used to obtain a physical description of the various storms affecting the area. This work is aimed at delineating the differences in storm seedabilities.

The project area, including the control areas, is over 200 miles long, on the longest axis. Consequently, the distances which must be covered to maintain a large number of recording gages on a weekly basis are tremendous. Some gages are accessible by passenger automobiles, while others require the use of four-wheel drive vehicles. Many of the target area gages are located on terrain which is so rugged that they must be serviced by helicopters. Still other gages, located on off-shore islands, can only be reached by boat or airplane.

There are four adjacent target areas. One is the south coast area of Santa Barbara County, a narrow strip of land between the Coast Range and the Pacific Ocean, and the second includes the upper and middle basins of the Santa Ynez River, north of the Coast Range. The third is the remainder of Santa Barbara County. The fourth constitutes a portion of Ventura County. There are three control areas; one to the north and west of the targets in the vicinity of San Luis Obispo, a second control area further north, lying between Cape San Martin and San Simeon, and the third control area is located in the Channel Islands lying off-shore and south of Santa Barbara.

Before the project was begun, an analysis of historic precipitation records indicated that it would require about 3 yr to obtain sufficient data to yield a significant answer. The third year of operation of the Santa Barbara Project was completed April 30, 1959. Evaluation of the third year and its combination with the two previous years was made available in September, 1959. It is apparent that 3 yr of data will not be enough to give a conclusive answer regarding the effectiveness of the cloud-seeding operations.

Table 1 shows the results of evaluation studies of the two completed years, 1957 and 1958. This table is extracted from a recent report of the statistical laboratory of the University of California.

In addition to the statistical evaluation of precipitation data, there are a number of other considerations which are of interest. There are certain factors, relating to the usefulness of this possible increase in water supply, which must be taken into account. In the first place, additional precipitation superimposed upon an existing heavy winter storm during a flood period would be of no practical use. It might be, in fact, the straw that "broke the camel's back" in causing flood damage. On the other hand, increased precipitation that could

be impounded in reservoirs, ground-water basins, snow pack, or in the soil mantle for carry-over into the growing season, would be useful and might be economically justified. Some evaluation has been made of these and other economic factors, but much remains to be done.

Early in the investigation, a brief study was made of the possible effects of an arbitrarily assumed 10% increase in precipitation on the total water supply

TABLE 1.—REGRESSION ANALYSIS

Period	Target <sup>a</sup>	Controls <sup>b</sup>	Average seeded in target, in inches	Analysis by Inches		Analysis by %/Inches	
				Expected seeded in target, in inches	% increase ascribable to seeding	Expected seeded in target, in inches	% increase ascribable to seeding
1957 Jan. 10 Apr. 30	T - Valley	A, B	0.429	0.208	+106	0.200	+115
		A	0.429	0.237	+ 81	0.228	+ 88
		B	0.327	0.206	+ 59	0.247	+ 32
	T - Coast	A, B	0.274	0.148	+ 85	0.145	+ 89
		A	0.274	0.179	+ 53	0.174	+ 58
		B	0.219	0.138	+ 59	0.163	+ 34
	SB - NW	A, B	0.228	0.067	+242	0.066	+247
		A	0.228	0.061	+272	0.060	+277
		B	0.185	0.082	+126	0.097	+ 91
	SB entire	A, B	0.320	0.145	+121	0.140	+128
		A	0.320	0.168	+ 90	0.162	+ 98
		B	0.251	0.146	+ 72	0.174	+ 44
1958, Jan. 1 Apr. 1	T - Valley	A, B	0.787	0.838	- 6	0.755	+ 4
		A	0.708	0.712	- 1	0.662	+ 7
		B	0.779	0.872	- 11	0.814	- 4
	T - Coast	A, B	0.502	0.482	+ 4	0.434	+ 16
		A	0.452	0.421	+ 7	0.388	+ 17
		B	0.487	0.539	- 10	0.516	- 6
	SB - NW	A, B	0.412	0.369	+ 12	0.331	+ 24
		A	0.371	0.315	+ 18	0.298	+ 25
		B	0.378	0.376	0	0.346	+ 9
	SB - entire	A, B	0.581	0.581	0	0.520	+ 12
		A	0.523	0.498	+ 5	0.461	+ 13
		B	0.569	0.612	- 7	0.573	- 1

<sup>a</sup> T - Valley: 4 stations; T - Coast: 4 stations; SB - NW: 3 stations; and SB - entire: 12 stations.

<sup>b</sup> Control A: 1 station; and Control B: 5 stations.

of an existing irrigation district, located in the east central portion of California's San Joaquin Valley. Works of the district include two storage dams and a diversion dam located on a major stream of the Sierra Nevada, together with conduits to transport water within the district. The drainage area above the diversion dam is about 1,500 miles and the 53-yr mean annual flow of the stream system is about 1,900,000 acre-ft. The district generates electric power and distributes it through its service area, surplus power being sold to

a private utility company. The total area included in the district is about 190,000 acres, of which about 150,000 acres are irrigated at any 1 yr. A wide variety of irrigated crops are grown in the district. The district lands have an average rainfall of about 10 in. to 12 in. per yr and a plentiful supply of irrigation water.

Studies of the effect of a 10% additional rainfall on the runoff to the tributary stream system reveal that the normal annual flow would be increased about 15%. This assumption was not modified by an effect, however, and this information should be taken into account; namely, that a long-time increase in the average precipitation would undoubtedly result in increased consumptive use of the watershed native vegetation. Neglecting this effect, it was indicated in a dry year when only 50% of normal precipitation would have occurred, a 10% increased precipitation would have resulted in a 28% increase in annual runoff, virtually all of which could have been regulated in the district's reservoirs.

The effect on the potential average yield of the stream system under normal conditions was the same as on the total runoff. During the 53-yr period from 1895 through 1947, the average yield of the stream would have been increased by about 15% by a 10% increase in rainfall.

In a prolonged water shortage the effect of a given percentage of increased precipitation on yield, when routed as resulting runoff through the existing conservation works, would be nearly as great in relative amount and of considerably greater monetary value. Reservoir operation studies indicate that the existing conservation works with a total storage capacity of about 700,000 acre-ft, including works of other districts and agencies, had a firm annual yield of approximately 900,000 acre-ft per yr during the critical dry period. The studies indicated that 10% additional precipitation would have increased the annual firm yield during this period to about 985,000 acre-ft or an increase of about 10%.

If the yield of the existing conservation facilities is increased by 10%, it could be assumed that approximately 10% additional lands could be brought under irrigation, or in the case of this district, about 15,000 acres. Gross farm income averages an estimated \$150 per irrigated acre. This income would produce a total benefit of about \$2,250,000 per yr. There would also be an increase in firm power production which, when based on the critical dry year, would amount to about \$50,000 per yr. This and similar studies for other areas, including dry farmed areas, indicate possible large economic benefits from weather modification operations.

#### FUTURE ACTIVITIES

Past legislatures have supported studies of weather modification in California as a part of the comprehensive and statewide investigation of all aspects of the State's water resources, requirements and development. The Santa Barbara Project is a logical phase of such studies. At the present time it is planned that this project will be continued until results are obtained which are statistically significant. The preliminary results indicate that another year or two of project operation will be required. In addition, the department has received legislature direction to conduct two additional weather modification experiments. These projects have not been selected either as to type or location, but it is intended that they will be put into operation when the need is indicated and when a proper research program has been formulated, with great consideration given to the results of the Santa Barbara Project.



# PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Department of Conditions of Practice are identified by the symbols (PP). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper number are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 2270 is identified as 2270(ST9) which indicates that the paper is contained in the ninth issue of the Journal of the Structural Division during 1959.

## VOLUME 85 (1959)

MARCH: 1960(HY3), 1961(HY3), 1962(HY3), 1963(IR1), 1964(IR1), 1965(IR1), 1966(IR1), 1967(SA2), 1968(SA2), 1969(ST3), 1970(ST3), 1971(ST3), 1972(ST3), 1973(ST3), 1974(ST3), 1975(ST3), 1976(WW1), 1977(WW1), 1978(WW1), 1979(WW1), 1980(WW1), 1981(WW1), 1982(WW1), 1983(WW1), 1984(WW1), 1985(SA2)<sup>c</sup>, 1986(IR1)<sup>c</sup>, 1987(WW1)<sup>c</sup>, 1988(ST3)<sup>c</sup>, 1989(HY3)<sup>c</sup>.

APRIL: 1990(EM2), 1991(EM2), 1992(EM2), 1993(HW2), 1994(HY4), 1995(HY4), 1996(HY4), 1997(HY4), 1998(SM2), 1999(SM2), 2000(SM2), 2001(SM2), 2002(ST4), 2003(ST4), 2004(ST4), 2005(ST4), 2006(PO2), 2007(HW2)<sup>c</sup>, 2008(EM2)<sup>c</sup>, 2009(ST4)<sup>c</sup>, 2010(SM2)<sup>c</sup>, 2011(SM2)<sup>c</sup>, 2012(HY4)<sup>c</sup>, 2013(PO2)<sup>c</sup>.

MAY: 2014(AT2), 2015(AT2), 2016(AT2), 2017(HY5), 2018(HY5), 2019(HY5), 2020(HY5), 2021(HY5), 2022(HY5), 2023(PL2), 2024(PL2), 2025(PL2), 2026(PP1), 2027(PP1), 2028(PP1), 2029(PP1), 2030(SA3), 2031(SA3), 2032(SA3), 2033(SA3), 2034(ST5), 2035(ST5), 2036(ST5), 2037(ST5), 2038(PL2), 2039(PL2), 2040(AT2)<sup>c</sup>, 2041(PL2)<sup>c</sup>, 2042(PP1)<sup>c</sup>, 2043(ST5)<sup>c</sup>, 2044(SA3)<sup>c</sup>, 2045(HY5)<sup>c</sup>, 2046(PP1), 2047(PP1).

JUNE: 2048(CP1), 2049(CP1), 2050(CP1), 2051(CP1), 2052(CP1), 2053(CP1), 2054(CP1), 2055(CP1), 2056(HY6), 2057(HY6), 2058(HY6), 2059(IR2), 2060(IR2), 2061(PO3), 2062(SM3), 2063(SM3), 2064(SM3), 2065(ST9), 2066(WW2), 2067(WW2), 2068(WW2), 2069(WW2), 2070(WW2), 2071(WW2), 2072(CP1)<sup>c</sup>, 2073(IR2)<sup>c</sup>, 2074(PO2)<sup>c</sup>, 2075(ST6)<sup>c</sup>, 2076(HY6)<sup>c</sup>, 2077(SM3)<sup>c</sup>, 2078(WW2)<sup>c</sup>.

JULY: 2079(HY7), 2080(HY7), 2081(HY7), 2082(HY7), 2083(HY7), 2084(HY7), 2085(HY7), 2086(SA4), 2087(SA4), 2088(SA4), 2089(SA4), 2090(SA4), 2091(EM3), 2092(EM3), 2093(EM3), 2094(EM3), 2095(EM3), 2096(EM3), 2097(HY7)<sup>c</sup>, 2098(SA4)<sup>c</sup>, 2099(EM3)<sup>c</sup>, 2100(AT3), 2101(AT3), 2102(AT3), 2103(AT3), 2104(AT3), 2105(AT3), 2106(AT3), 2107(AT3), 2108(AT3), 2109(AT3), 2110(AT3), 2111(AT3), 2112(AT3), 2113(AT3), 2114(AT3), 2115(AT3), 2116(AT3), 2117(AT3), 2118(AT3), 2119(AT3), 2120(AT3), 2121(AT3), 2122(AT3), 2123(AT3), 2124(AT3), 2125(AT3).

AUGUST: 2126(HY8), 2127(HY8), 2128(HY8), 2129(HY8), 2130(PO4), 2131(PO4), 2132(PO4), 2133(PO4), 2134(SM4), 2135(SM4), 2136(SM4), 2137(SM4), 2138(HY8)<sup>c</sup>, 2139(PO4)<sup>c</sup>, 2140(SM4)<sup>c</sup>.

SEPTEMBER: 2141(CO8), 2142(CO8), 2143(CO8), 2144(HW3), 2145(HW3), 2146(HW3), 2147(HY9), 2148(HY9), 2149(HY9), 2150(HY9), 2151(IR3), 2152(ST7)<sup>c</sup>, 2153(IR3), 2154(IR3), 2155(IR3), 2156(IR3), 2157(IR3), 2158(IR3), 2159(IR3), 2160(IR3), 2161(SA5), 2162(SA5), 2163(ST7), 2164(ST7), 2165(SU1), 2166(SU1), 2167(WW3), 2168(WW3), 2169(WW3), 2170(WW3), 2171(WW3), 2172(WW3), 2173(WW3), 2174(WW3), 2175(WW3), 2176(WW3), 2177(WW3), 2178(CO8)<sup>c</sup>, 2179(IR3)<sup>c</sup>, 2180(HW3)<sup>c</sup>, 2181(SA5)<sup>c</sup>, 2182(HY9)<sup>c</sup>, 2183(SU1)<sup>c</sup>, 2184(WW3)<sup>c</sup>, 2185(PP2)<sup>c</sup>, 2186(ST7)<sup>c</sup>, 2187(PP2), 2188(PP2).

OCTOBER: 2189(AT4), 2190(AT4), 2191(AT4), 2192(AT4), 2193(AT4), 2194(EM4), 2195(EM4), 2196(EM4), 2197(EM4), 2198(EM4), 2199(EM4), 2200(HY10), 2201(HY10), 2202(HY10), 2203(PL3), 2204(PL3), 2205(PL3), 2206(PO6), 2207(PO6), 2208(PO6), 2209(PO6), 2210(SM5), 2211(SM5), 2212(SM5), 2213(SM5), 2214(SM5), 2215(SM5), 2216(SM5), 2217(SM5), 2218(ST8), 2219(ST8), 2220(EM4), 2221(ST8), 2222(ST8), 2223(ST8), 2224(HY10), 2225(HY10), 2226(PO6), 2227(PO6), 2228(PO6), 2229(ST8), 2230(EM4), 2231(EM4), 2232(AT4)<sup>c</sup>, 2233(PL3)<sup>c</sup>, 2234(EM4)<sup>c</sup>, 2235(HY10)<sup>c</sup>, 2236(SM5)<sup>c</sup>, 2237(ST8)<sup>c</sup>, 2238(PO6)<sup>c</sup>, 2239(PO6), 2240(PL3).

NOVEMBER: 2241(HY11), 2242(HY11), 2243(HY11), 2244(HY11), 2245(HY11), 2246(SA6), 2247(SA6), 2248(SA6), 2249(SA6), 2250(SA6), 2251(SA6), 2252(SA6), 2253(SA6), 2254(SA6), 2255(SA6), 2256(ST9), 2257(ST9), 2258(ST9), 2259(ST9), 2260(HY11), 2261(ST9)<sup>c</sup>, 2262(ST9), 2263(HY11), 2264(ST9), 2265(HY11), 2266(SA6), 2267(SA6), 2268(SA6), 2269(HY11)<sup>c</sup>, 2270(ST9).

DECEMBER: 2271(HY12)<sup>c</sup>, 2272(CP2), 2273(HW4), 2274(HW4), 2275(HW4), 2276(HW4), 2277(HW4), 2278(HW4), 2279(HW4), 2280(HW4), 2281(IR4), 2282(IR4), 2283(IR4), 2284(IR4), 2285(PO8), 2286(PO8), 2287(PO8), 2288(PO8), 2289(PO8), 2290(PO8), 2291(PO8), 2292(SM6), 2293(SM6), 2294(SM6), 2295(SM6), 2296(SM6), 2297(WW4), 2298(WW4), 2299(WW4), 2300(WW4), 2301(WW4), 2302(WW4), 2303(WW4), 2304(WW4), 2305(ST10), 2306(CP2), 2307(CP2), 2308(ST10), 2309(CP2), 2310(HY12), 2311(HY12), 2312(PO8), 2313(PO8), 2314(ST10), 2315(HY12), 2316(HY12), 2317(HY12), 2318(WW4), 2319(SM6), 2320(SM6), 2321(ST10), 2322(ST10), 2323(HW4)<sup>c</sup>, 2324(CP2)<sup>c</sup>, 2325(SM6)<sup>c</sup>, 2326(WW4)<sup>c</sup>, 2327(IR4)<sup>c</sup>, 2328(PO8)<sup>c</sup>, 2329(ST10)<sup>c</sup>, 2330(CP2).

## VOLUME 86 (1960)

JANUARY: 2331(EM1), 2332(EM1), 2333(EM1), 2334(EM1), 2335(HY1), 2336(HY1), 2337(EM1), 2338(EM1), 2339(HY1), 2340(HY1), 2341(SA1), 2342(EM1), 2343(SA1), 2344(ST1), 2345(ST1), 2346(ST1), 2347(ST1), 2348(EM1)<sup>c</sup>, 2349(HY1)<sup>c</sup>, 2350(ST1), 2351(ST1), 2352(SA1)<sup>c</sup>, 2353(ST1)<sup>c</sup>, 2354(ST1).

FEBRUARY: 2355(CO1), 2356(CO1), 2357(CO1), 2358(CO1), 2359(CO1), 2360(CO1), 2361(PO1), 2362(HY2), 2363(ST2), 2364(HY2), 2365(SU1), 2366(HY2), 2367(SU1), 2368(HY2), 2369(HY2), 2370(SU1), 2371(HY2), 2372(PO1), 2373(SM1), 2374(HY2), 2375(PO1), 2376(HY2), 2377(CO1)<sup>c</sup>, 2378(SU1), 2379(SU1), 2380(SU1), 2381(HY2)<sup>c</sup>, 2382(ST2), 2383(SU1), 2384(ST2), 2385(SU1)<sup>c</sup>, 2386(SU1), 2387(SU1), 2388(SU1), 2389(SM1), 2390(ST2)<sup>c</sup>, 2391(SM1)<sup>c</sup>, 2392(PO1)<sup>c</sup>.

MARCH: 2393(IR1), 2394(IR1), 2395(IR1), 2396(IR1), 2397(IR1), 2398(IR1), 2399(IR1), 2400(IR1), 2401(IR1), 2402(IR1), 2403(IR1), 2404(IR1), 2405(IR1), 2406(IR1), 2407(SA2), 2408(SA2), 2409(HY3), 2410(ST3), 2411(SA2), 2412(HW1), 2413(WW1), 2414(WW1), 2415(HY3), 2416(HW1), 2417(HW3), 2418(HW1)<sup>c</sup>, 2419(WW1)<sup>c</sup>, 2420(WW1), 2421(WW1), 2422(WW1), 2423(WW1), 2424(SA3), 2425(SA2)<sup>c</sup>, 2426(HY3)<sup>c</sup>, 2427(ST3)<sup>c</sup>.

c. Discussion of several papers, grouped by divisions.

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**PART 2**

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PART 2

*Your attention is invited*

**NEWS  
OF THE  
IRRIGATION  
AND  
DRAINAGE  
DIVISION  
OF  
ASCE**



**JOURNAL OF THE IRRIGATION AND DRAINAGE DIVISION  
PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS**



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## DIVISION ACTIVITIES

### IRRIGATION AND DRAINAGE DIVISION

#### Proceedings of the American Society of Civil Engineers

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#### NEWS

March, 1960

#### PURPOSE OF THE IRRIGATION AND DRAINAGE DIVISION

"To promote advancement in thought and practice in the field, to clarify fundamental principles, to disseminate knowledge of current practice and the results obtained therefrom and to bring about closer acquaintance of those engaged in irrigation and drainage engineering. The field of work of the Irrigation and Drainage Division includes all engineering concerned with the application of water to land or the removal of water therefrom and all of the technical, economic, and social aspects of the association of engineering with these problems. In brief, it covers all phases of irrigation, drainage, and reclamation of lands." Executive Committee, Irrigation and Drainage Division, ASCE

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2001 S. Madison St., Denver 10, Colo.

John Rinne, Contact member from Board of Direction

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3223 S. Columbine St., Denver 10, Colo.

#### CALENDAR OF COMING MEETINGS

March 7-11, 1960. National Convention, ASCE, Jung Hotel, New Orleans, La.

The Irrigation and Drainage Division has planned four half-day sessions on the general theme, "Humid Area Water Problems." The first session will be devoted to papers by the Research Committee, the second and third to

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papers from the Committee on Irrigation and Drainage Practices in Humid Areas, and the fourth half-day session to subjects and topics of local interest.

June 20-24, 1960. National Convention, ASCE, Reno, Nevada. The Irrigation and Drainage Division sessions at this convention will be on the theme, "De-salinization of Water," and will constitute our technical conference for 1960. Two half-day sessions on de-salinization will highlight the theme, and two additional half-day sessions will be filled with papers dealing with irrigation and drainage problems of the Pacific Coast and the Great Basin. In addition the I & D Division hopes to sponsor one of the convention luncheons, which would feature a luncheon talk on, "The Economics of De-salinization of Water."

August 17-19, 1960. Annual Conference, Hydraulics Division, ASCE. University of Washington, Seattle, Wash.

October 10-14, 1960. National Convention, ASCE, Hotel Statler, Boston, Mass.

April 10-14, 1961. National Convention, ASCE, Phoenix, Ariz. The Irrigation and Drainage Division plans to sponsor four half-day sessions on the theme, "Water Conservation in Arid Areas." These sessions will constitute the Irrigation and Drainage Division technical conference for 1961. A number of papers already have been proposed for this convention, and any further suggestions for papers should be sent to Dean Christensen, Chairman of the Committee on Session Programs.

In the future: The Irrigation and Drainage Division also plans to sponsor technical sessions at the Houston Convention, in February, 1962, the Omaha Convention in May 1962 and the Detroit Convention in October 1962. Send your suggestions for subjects to be discussed at these meetings to Herbert Prater, Vice-Chairman of the Committee on Session Programs.

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Chairmen of other standing committees of the Irrigation and Drainage Division are:

Committee on Publications: Dean F. Peterson, Jr., Utah State University, Logan, Utah.

Committee on Cooperation with Local Section: S. Mark Davidson, 2432 S. Jasmine St., Denver 22, Colo.

Committee on Consolidation and Progressive Betterment of Old Irrigation Systems: A. Alvin Bishop, Utah State University, Logan, Utah.

Committee on Drainage of Irrigated Lands: E. W. Elliott, 9801 Salem Road, N. E. Albuquerque, N. M.

Committee on Ground Water: Harvey O. Banks, Dept. of Water Resources, Sacramento, Calif.

Committee on Irrigation and Drainage Practices in Humid Areas: Marion C. Boyer, 1330 W. Michigan St., Room 377, Indianapolis, Indiana.

Task Group on Water Rights Laws in States in Humid Areas: James I. Seay Jr., 516 Goodwyn Inst. Bldg., Memphis, Tenn.

Committee on Research: Gerald B. Keese, Bureau of Indian Affairs, Washington, D. C.

Committee on Water Supply and Conservation: Harry F. Blaney, 215 West 7th St., Los Angeles 14, Calif.

Task Group on Methods of Conserving Water: Arthur E. Bruington, 636 W. Hermosa Avenue, San Gabriel, Calif.

Task Group on Consumptive Use of Water by Irrigated Crops and Native Vegetation: Harry F. Blaney.

Task Group on Re-Use of Drainage Water and Water Reclamation: Lloyd E. Myers, Jr., Box 815C, Route 2, Tempe, Ariz.

Task Group on Water Management: Leonard Schiff, 2219 Lester St., Bakersfield, Calif.

Task Group of Waterquality: P. H. McGauhey, 6819 Snowden Ave. El Cerrito, Calif.

These men are constantly in need of help from other society members. Why not volunteer your talents to the one heading the committee that is working in your field of interest?

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#### Actions of the Executive Committee

The Division executive committee met in Los Angeles, November 11 and 12, 1959. All members of the committee, including the new contact member from the Board of Direction, Mr. John E. Rinne, were present.

Two new members were appointed to the Committee on Publications: Dr. Eldred R. Harrington of Albuquerque, N. M., and Daryl B. Simons, of Fort Collins, Colo. Mr. Rinne outlined some of the recent amendments to the society's publication policies. The most important of the new rules is that only papers that can be recommended for publication in Transactions will be included in the Journals, and that all Journal papers that receive creditable discussion will be published in the new Transactions. Prospective authors may obtain copies of the revised policies from ASCE headquarters.

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#### Irrigation Engineer Tours Europe and Asia

Harry F. Blaney, Irrigation Engineer, U. S. Department of Agriculture, Los Angeles, California, recently completed a 5-month tour inspecting irrigated areas in Greece, Turkey, Israel, Pakistan, India, Thailand, Japan and Hawaii. Three months were spent in Israel evaluating irrigation research and water utilization for the U. S. International Cooperation Administration. Last year Mr. Blaney was appointed Chairman of the Water Conservation Committee of the Irrigation and Drainage Division of the ASCE.

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#### COLORADO IRRIGATION AND DRAINAGE DIVISION NOTES

The Irrigation and Drainage Division of the Colorado Section, ASCE, has recently heard about planning irrigation systems in the United States and prospects for large-scale developments in Ethiopia.

At its January 27, 1960, meeting the topic was, "Soil-Moisture Relationships in Planning an Irrigation System." Orville A. Parsons, SCS Soil Scientist from Lamar, Colorado, was the speaker.

In the November 25, 1959 meeting, sponsored by the Colorado Section's Hydraulics Division, the speaker was Herbert S. Riesbol, F. ASCE, Chief, Hydrology Branch, Bureau of Reclamation, Denver. His subject, "Blue Nile Water Resources Development in Ethiopia," was well illustrated with maps and colored slides, taken by Mr. Riesbol and selected to depict the geography, culture, development, and prospects for that country. Another long-time member of the Society, Donald P. Barnes, currently is heading up an engineering mission to prepare plans for the Blue Nile Development.

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### CONVENTION PROGRAMS

Would YOU like to present a paper? Do YOU have a problem you would like to hear discussed? Here is YOUR opportunity to participate in planning the I & D DIVISION technical sessions at future conventions. Take time to fill in and mail the following form:

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I would like to present a paper on \_\_\_\_\_

\_\_\_\_\_  
(Subject)

I would like to hear discussion of the following subject \_\_\_\_\_

I suggest \_\_\_\_\_ as a possible author of a paper on  
(name)

\_\_\_\_\_  
(subject)

\_\_\_\_\_  
Name

\_\_\_\_\_  
mailing address

\_\_\_\_\_  
Mail to Herbert E. Prater, 2001 So. Madison St.,  
Denver 10, Colorado



